The Space Elevator
NIAC Phase II Final Report

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Executive Summary

This document in combination with the book *The Space Elevator* (Edwards and Westling, 2003) summarizes the work done under a NASA Institute for Advanced Concepts Phase II grant to develop the space elevator. The effort was led by Bradley C. Edwards, Ph.D. and involved more than 20 institutions and 50 participants at some level.

The objective of this program was to produce an initial design for a space elevator using current or near-term technology and evaluate the effort yet required prior to construction of the first space elevator.

Prior to our effort little quantitative analysis had been completed on the space elevator concept. Our effort examined all aspects of the design, construction, deployment and operation of a space elevator. The studies were quantitative and detailed, highlighting problems and establishing solutions throughout. It was found that the space elevator could be constructed using existing technology with the exception of the high-strength material required. Our study has also found that the high-strength material required is currently under development and expected to be available in 2 years.

Accepted estimates were that the space elevator could not be built for at least 300 years. Colleagues have stated that based on our effort an elevator could be operational in 30 to 50 years. Our estimate is that the space elevator could be operational in 15 years for $10B. In any case, our effort has enabled researchers and engineers to debate the possibility of a space elevator operating in 15 to 50 years rather than 300.

This program has also grabbed the public attention resulting in hundreds of television, radio and newspaper spots around the world. These have included the front page of several prominent publications (Canada's *National Post*, *Science News*, *Seattle Times*, *Ad Astra*), live interviews and features on CNN and BBC, and hundreds of radio and newspaper spots including the *New York Times* and a feature in *Wired* magazine. Dr. Edwards has briefed NRO, NASA HQ, AFRL, FCC, FAA, members of congress, and various public, academic and private institutions. A conference with 60 attendees was held to examine all aspects of the concept (technical, financial, legal, health,…).

Various possible follow-on funding sources and organizational strategies have been examined. Dr. Edwards has accepted a position as Director of Research at the Institute for Scientific Research where the space elevator effort will continue. This opportunity immediately gives the effort resources, technical and business staff, political connections and credibility.

This program was the first real quantitative evaluation of the space elevator and has created an active area of research and possibly put us on the road to constructing the first elevator. This was the first step toward building a truly economical method for accessing space.

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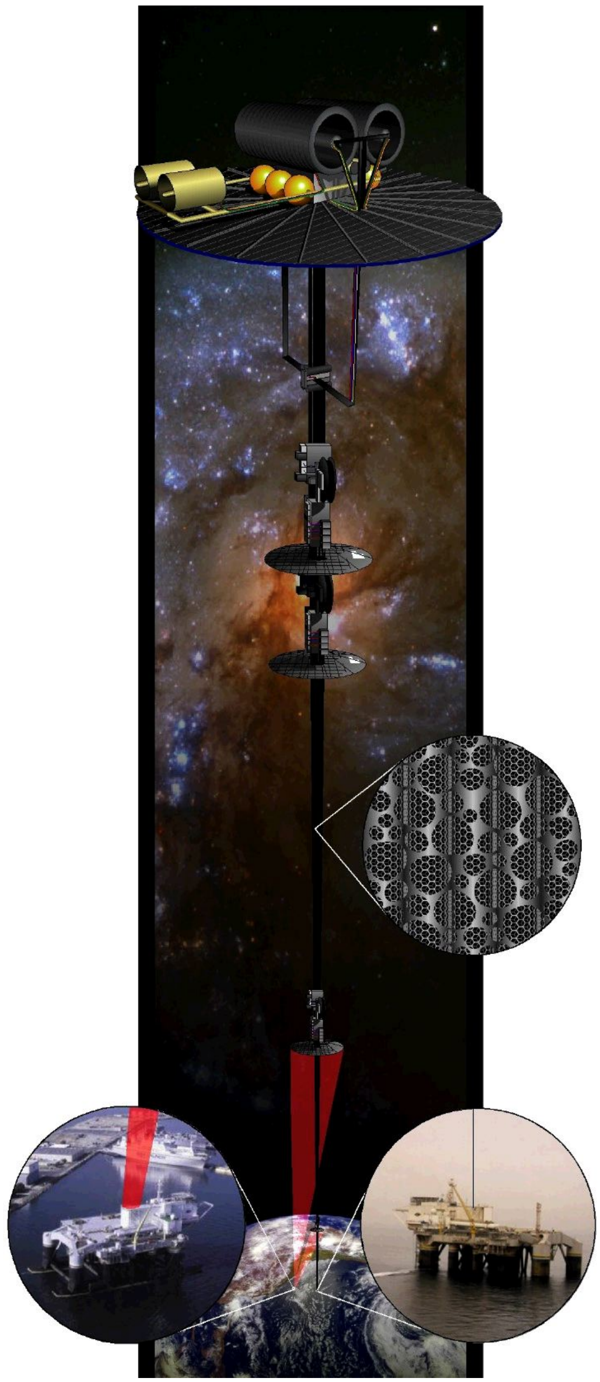
Introduction

Man has always dreamed of climbing to the heavens. A thousand years ago this may have manifested itself in a king's construction of a tall stone structure reaching hundreds of feet into the air. A hundred years ago the building may have been taller and could be done by a wealthy individual but was not much closer to reaching the heavens. With the advent of the space age, some innovative people proposed a space elevator, a cable extending from Earth to space that could be ascended by mechanical means. The concept was also generally discarded because there was no material strong enough to construct the proposed cable. The idea of a space elevator was not realistically viable until after 1991 when carbon nanotubes were discovered. With the discovery of carbon nanotubes and the developments of the previous decades the space elevator could now be considered.



Starting from this point we began our NIAC Phase I study. In our Phase I effort we laid out the general concept, the basic design, the physical challenges and how to address the issues. We made a good start on the first draft of a viable system. Under Phase I, limited by time and funding, we were unable to get into many of the critical details of the system, its components or to test any of the designs. Our NIAC Phase I Final Report became the baseline for our Phase II effort and the foundation for many researchers around the world to begin independent studies on various aspects of the space elevator.

Our Phase I effort was strictly technical, few associated areas like politics, funding, regulations, health, public support or the media were considered. And although the technical feasibility of the program is critical it is only part of the entire picture.

The NIAC Phase II effort described in this final report and our published book, *The Space Elevator*, continue on where the Phase I left off.

Proposed Studies

The Phase II effort, reported on in this document, was proposed to NIAC in November 2000 and begun in March of 2001. The proposed effort was extensive and covered all aspects of the space elevator. In our proposal we stated:

> *Our Phase II plan is to attack the remaining questions and begin laboratory testing of the critical components and designs. At the end of Phase II we will have design scenarios backed with experimental data to show the feasibly of the space elevator, allow for defendable estimates of when the space elevator can be constructed and define the efforts that are required to complete the design and construction of a space elevator. This analysis is critical for any future decisions on the space elevator and will help NASA make sound choices on future funding thrusts in this area.*

Our proposal also listed the primary areas of effort would relate to:

- Large-scale nanotube production
- Cable production
- Cable design
- Power beaming system
- Weather at the anchor site
- Anchor design
- Environmental impact
- Placing payloads in Earth orbit
- Elevators on other planets
- Possible tests of system
- Major design trade-offs
- Budget estimates
- Independent review of program

We gave details in the proposal of the effort in each of these areas. As the work began and we made progress in each area, it was found that our detailed plans needed to be modified. For example, our ribbon design, variations on the design and the tests that we proposed soon changed as we saw how the carbon nanotube composite development was progressing. The ribbon went from a sheet to a set of individual fibers held together by interconnects and thus the tests required modification as well. The point being is that several items proposed were replaced as designs changed and numerous items were added to the effort. We had considered writing this final report as a list of proposed efforts with the matching accomplishments but decided that would not work. In addition, as part of our effort to disseminate we published an extensive book on the technical design of the system and repeating that manuscript here has limited value.

What we hope to do in our publications is to put forth a convincing case that we have indeed defined a viable, defendable space elevator design and completely addressed the challenges that its construction and operation will face.

Results and Implications

When we sent in our NIAC Phase I report, it was 13 Megabytes, 85 pages and was unwieldy to distribute. Based on input from colleagues we have produced a slightly different final report for Phase II. At the end of January, our book, *The Space Elevator*, became publicly available through Amazon.com. This is a 288-page compilation of most of the technical work to date on this project. We will not try to repeat this manuscript here but reference it repeatedly. What will be in this final report is the rest of the work that doesn't appear in the book. The behind the scenes efforts, how all of the work fits together and how this together illustrates that a space elevator can be constructed in the near future.

Organization and Administrative

At the end of Phase I the space elevator program consisted of one primary individual, Dr. Bradley C. Edwards, and a dozen collaborators around the U.S. With the Phase II funding and the growing interest in the program, the effort grew in participants and scope.

There was considerable organization that occurred during the course of Phase II to deal with the growing and changing program. Media attention needed to be address and directed. Volunteers needed to be met and implemented. New associates needed to be organized into a useful team. New segments of the program needed to be structured and directed. This became a drain on the program but also enabled much more to be produced with the NIAC funding.

Much of the early work was conducted out of Dr. Edwards' residence but to facilitate the effort, midway through Phase II, office space in Seattle was acquired. This space allowed for meetings to be held and work to be more easily conducted.

One of the other organizational or administrative aspects of the program that came up in the Phase II was the issue of patents and patentable work. Much of our space elevator effort has been original work and designs that could be patented. However, in understanding the problem and our desire to get the system built not to make money from it we have largely ignored the patent process. In publishing our NIAC Phase I report on the web we have placed all of that work in the public domain, eliminating the possibility of anyone patenting the system. We did decide in Phase II to file for one patent on the ribbon design though we have published our work on that as well since filing. This patent is note so much to tie up the technology as it is to eliminate the possibility of someone else limiting its availability and to assist in finding funding for further efforts.

Collaborations

The space elevator is a large project no matter how you look at it. Full development of such projects requires comparably large development programs. And though the $570k that NIAC has given us for funding is substantial, especially for an advanced technology development program, it is not sufficient to complete the development of a space elevator design unless it is heavily leveraged. In our effort we have attempted to leverage the NIAC funds by incorporating as many collaborators as possible, almost always unpaid. This expanded team allows us to address many different questions efficiently. And although many collaborations fail to produce any useful results the net result on our program was positive. Also as a result of our pursuit of collaborations many researchers are aware of the work being done and are getting involved in various aspects. Independent work has sprung up at different locations, funders are considering this area, thesis students are working on different aspects of the elevator, and several conferences are now considering including sessions on the space elevator.

Our collaborators have come from worldwide institutions including but are not limited to:

3M Corporation	Los Alamos National Laboratory
Art Anderson Associates	Nanoledge
Augur Aeronautical Centre	NASA - Johnson Space Center
Bennett Optical / Compower	Owens-Corning
Carbon Nanotechnologies Inc.	Princeton University
Lockheed Martin	ReyTech
European Space Agency	Rutgers University
Flight Materials Group	U of Mississippi – Space Law Center
Foster-Miller, Inc.	T. Y. Lin International
Harvard University	Thomas Jefferson National Laboratory
HighLift Systems	University of Kentucky

Due to our progress, the media attention the space elevator has received has increased by factors of hundreds. This attention has required resources but has also helped our program. During the Phase II we have attracted numerous volunteers ranging from interested non-technical public to world experts in critical areas. We have not recorded all of these offers of assistance but have attempted to utilize them as well as possible. The most productive of these collaborations are discussed at various places in this final report and in our book.

<u>Carbon Nanotubes and Carbon Nanotube Composites</u>

The most critical element in the development of the space elevator is the design, construction and testing of the carbon nanotube ribbon segments. It is absolutely critical to have ultra-high-strength material (100 GPa) in a form we can use. As we have stated many times, steel is not strong enough, neither is Kevlar, carbon fiber, spider silk or any other material other than carbon nanotubes. Fortunately for us, carbon nanotube research is extremely hot right now and it is progressing quickly to commercial production. A division of Mitsui will be producing about 10 tons of carbon nanotubes each month starting in the next month or two. We have initiated discussions with Mitsui and they will be sending us 100 grams of carbon nanotubes to examine. (We have purchased CNTs for $700/gm. Mitsui will be sending us the 100 grams for free. Their expected sale price is $100/kg!) The quality of these nanotubes is unknown at the moment but based on laboratory production of nanotubes it is expected to be high. Early measurements of carbon nanotubes made in academic labs found them to have tensile strengthes of 63 GPa. Their theoretical tensile strength is 300 GPa.

In this program we have purchased roughly 30 grams of carbon nanotubes at a cost of $700/gm. First, all of the carbon nanotube material was characterized in terms of purity (amorphous carbon, Fe, ...), alignment, multi or single-walled and SEM and TEM visualization. It was found that much of the carbon nanotube material that has been available has wildly varying properties depending on who made it and the batch. The TEM and SEM images of our CNT's from Carbon Nanotechnologies Inc. (CNI) and Cheng in China showed that the Cheng nanotubes produced by electric arc discharge were higher quality and better aligned than the ones produced by gas decomposition at CNI. Some residual catalyst (Fe) and some amorphous carbon was found in several of the samples but they can be cleaned by various techniques.

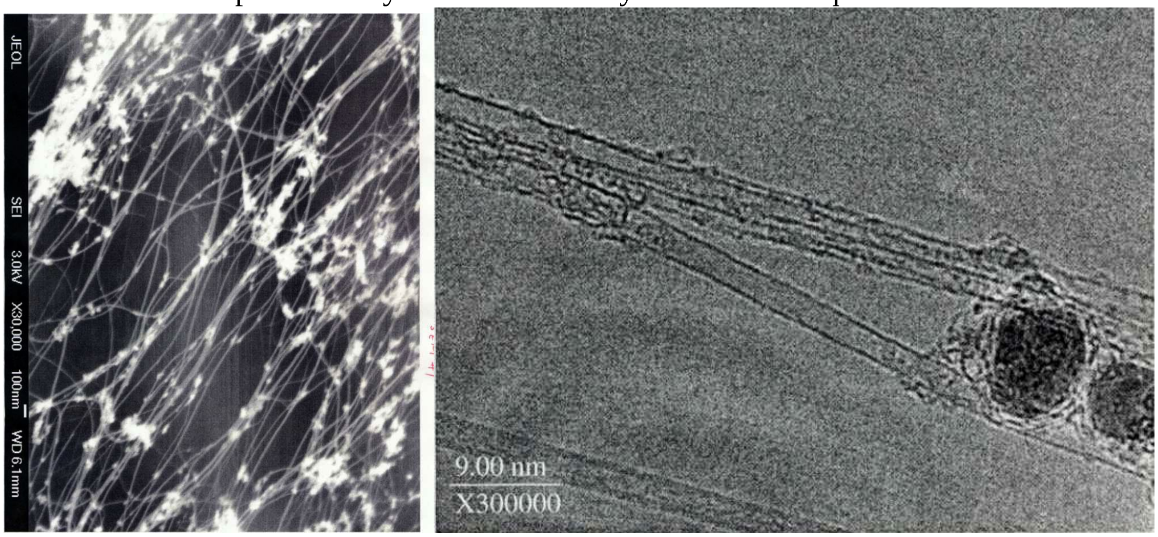


Figure 1: SEM and TEM images of some of our carbon nanotubes.

The material we purchased was used to develop composite materials to better understand how to make the process work and for health issue testing. The addition of 100 grams from Mitsui and their intention to sell nanotubes at $100/kg will push research in structural applications and allow us to move several efforts forward. One of the current hurdles to carbon nanotube composite development is the high cost of the carbon nanotubes. Mitsui will eliminate this hurdle.

And although the development of carbon nanotubes is progressing very quickly this is not the entire story for use in the space elevator or any structural application. Carbon nanotubes have lengths of tens to hundreds of microns, far short of any macroscopic requirement. However, glass and carbon fibers also have limited use in their raw form but as part of a composite they are extremely versatile for structural applications. The key is to get the carbon nanotubes into a composite.

To move this along, we have been working with Foster Miller Inc., University of Kentucky, Carbon Nanotechnologies Inc., Hui-Ming Cheng (China), Reytech, University of Washington, University of Oklahoma, Los Alamos National Laboratory, and others to encourage collaborative efforts and improve progress in this area.

Initially we had a specific design for a ribbon that consisted of a sheet of carbon nanotube composite. As will be seen below and in our book we have gone to a ribbon with individual small fibers. This change was partially due to an improved understanding of the degradation of the ribbon and partially from a better understanding of the production of carbon nanotube composites. We are now looking to develop a technique for producing ultra-strong individual fibers roughly 10 microns in diameter and lengths of many meters to kilometers.

The challenges to making ultra-strong carbon nanotube composites are:

1. Uniform dispersion and alignment of the nanotubes in the matrix
2. Formation of a smooth and defect free fiber

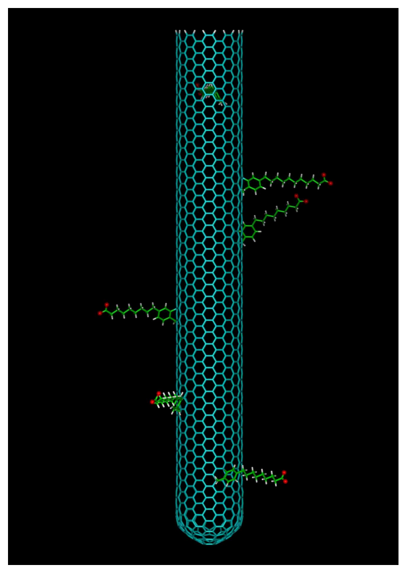
3. Efficient stress transfer from the matrix to the nanotube
4. Attaining high nanotube loadings

The reason for these challenges that are not a problem in conventional composites is the size and perfection of the carbon nanotubes and the high performance we are attempting to achieve. Each of these challenges is being addressed and several have been solved.

1. <u>Uniform dispersion and alignment of the nanotubes in the matrix</u> For optimal tensile strength, the nanotubes must be perfectly dispersed and perfectly aligned axially to the fiber. We have been able to disperse nanotubes into the matrix uniformly as individual tubes and are found to align along the stress field. This process is often matrix dependent.

2. <u>Formation of a smooth and defect free fiber</u> Most of the problems we have encountered in producing high strength fibers have been a result of the poor surface quality of the product fibers. It is essential to produce a fiber with minimal surface imperfections. As the loading of nanotubes in the matrix is increased, the result fibers have a very rough surface that can be attributed to the increasing melt strength of the nanotube doped materials. This surface roughness acts as a defect site for failure initiation under load. Techniques to overcome this problem include multicore extrusion or post extrusion dip coatings with matrix to yield a fiber with a smooth surface.

3. <u>Efficient stress transfer from the matrix to the nanotube</u> The outer surface of a nanotube is a very smooth graphite surface, not conducive to good matrix adhesion. To achieve maximal strength, very efficient stress transfer from the matrix to the nanotube reinforcement is necessary. This will only be achieved utilizing nanotubes either directly or indirectly modified to improve the interfacial adhesion. Methods include both direct chemical functionalization of the nanotube (shown at right) as well as selected compounds to be used as sizing agents. These chemistries must be tailored for each specific matrix used, with the ultimate goal of chemically bonding the nanotubes within the matrix.



4. <u>Attaining high nanotube loadings</u> To acheive high-strength materials it will be necessary to have a high loading of nanotubes in the fiber, up to 50%. Because of this, modifications of the fiber forming process will be necessary in order to allow spinning of defect free fibers at such high loadings.

The University of Kentucky has published and patented on fibers 5 km long with 1% carbon nanotube loading that achieved a tensile strength increase from 0.7 GPa to 1.1 GPa. Recent results have included producing fibers with tensile strengths of 5GPa with ~5% CNT loading. Steel has a strength of 3 GPa and Kevlar is at 3.7 GPa. This process used multi-walled carbon nanotubes. This implies a roughly 100 GPa carbon nanotube strength or an interfacial adhesion roughly 1/3 of theoretical. However, we must remember that in the current process only the outer nanotubes are being functionalized and attached to, the inner tubes are not being fully utilized. Understanding this implies that by finding a method to utilize the inner shells would enable production of material performing close to theoretical maximum. A complimentary technique now being developed at Rensealler Polytechnic Institute allows for the pinning of the walls in the multi-walled tubes together so that all of the tubes can be used. Techniques at Foster Miller will also allow for dispersion and implementation of the carbon nanotubes in the composite at much higher loadings. Loadings over 25% have been demonstrated and higher levels are possible. By combining these techniques the resulting material should have a tensile strength near theory of 150 GPa for 50% loading. Material at 12 GPa (4 times stringer than steel) is expected in the coming months and the full strength materials should be available within two years at the current research rate.

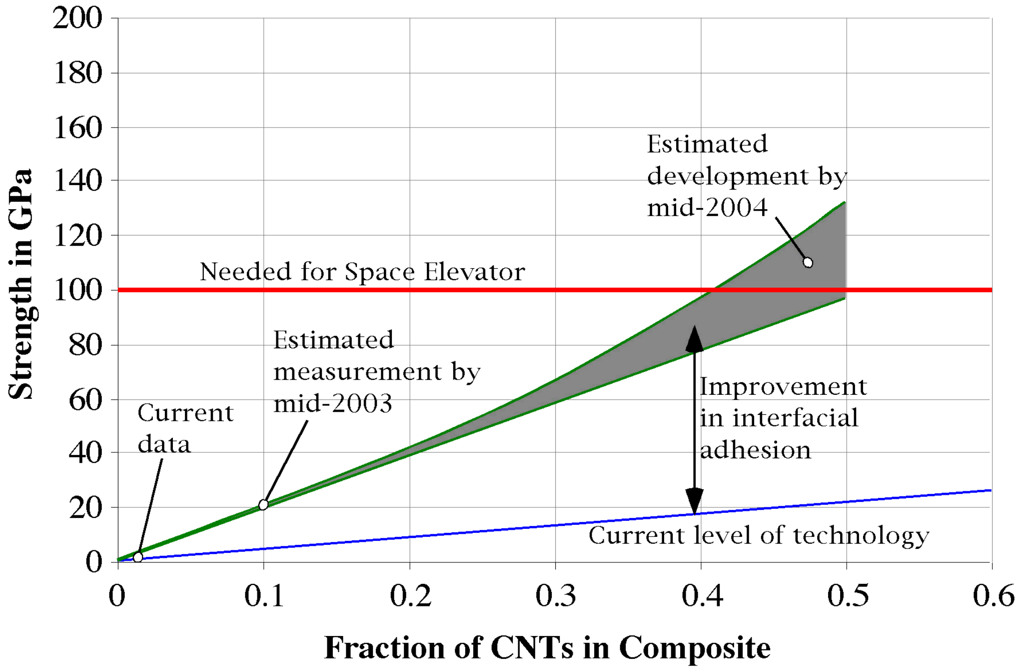


Figure 2: Current state and calculated performance curves for upcoming developments in carbon nanotube composites.

<u>Power beaming</u>

We have continued our discussions with Hal Bennett of Bennett Optical / Compower. With proper funding they hope to have an operating system in 3.5 years. Bennett is also very interested in participating in our proposed feasibility tests. In conjunction with George Neal at Thomas Jefferson National Lab they propose to supply us with an operating and a 1 m optic to supply the power beaming component of the feasibility test.

The best currently designed system for both demonstrating and utilizing the space elevator concept is the laser designed by Lawrence Berkeley National Laboratory and now waiting to be built. It utilizes the sophisticated room temperature accelerator design built for the Stanford Linear Accelerator Complex (SLAC). The SLAC system at Stanford has been operating continuously for over two years now with great success. The laser designed using this technology will operate at 0.84 μm with an initial output power of 200 kW or upgradeable to 1,000 kW (The injector is now being tested at 350kW). It will beam laser power to space using a 15 m diameter beam director. Birds and airplanes can then fly through the laser beam without harm and at focus in space the average beam intensity on the solar panels is ten times that of the sun. Once started, this power beaming complex will require 4-5 years to build.

The laser beam director will have an adaptive optic primary mirror one meter in diameter for focusing and tracking. The lightweight beam director mirrors are expected to be graphite impregnated cyanate ester composites fabricated using the technology now being demonstrated by Bennett Optical Research under a NASA two-year, SBIR Phase II contract. The composite mirrors will be built to the same performance specifications as the Zerodur or ULE mirrors normally used in large telescopes. The coefficient of thermal expansion of the composite is comparable to Zerodur or ULE and Young's modulus, as measured at Bennett Optical Research on samples furnished by Composite Mirror Applications Inc. of Tucson, AZ, is slightly greater for the composite material than for either of the glasses. Moreover, the composite material is not brittle, and when an adaptive optic mirror is used, the faceplate can be remarkably thin. The mirror influence function[21] which determines how accurately the adaptive optic mirror surface matches the wavefront distortion induced by the atmosphere, can thus match an atmospheric correlation or Fried coefficient[22] only a few centimeters in length. The requirements on "seeing" which have limited observatories to very high locations and keep them from functioning well under turbulent atmospheric conditions are thus greatly relaxed. The composite "transfer mirrors" are made using a replication process, can have scattered light levels comparable to superpolished ULE or Zerodur, excellent optical figures, and cost a fraction of what the more conventional mirrors do. Bennett optical now has a completed facility to begin producing mirrors for this and its other programs.

The other issue of the laser power beaming that has been addressed is the stability and size issues of placing this system on an ocean-going platform. The current system requires 150 m of straight path real estate. Our initial baselined platform was 137 m in length though part of this was not usable. Our new anchor design (below and in *The Space Elevator*) can accommodate this length requirement and has the stability required for supporting the laser and adaptive optics.

We have examined the design aspects of the power receiver on the climber and worked out the thermal and electrical efficiency of the design. In conjunction with this we have received specifications and sample GaAs solar cells. Based on the measured specifications for the solar cells we received we can expect 80% light to electricity conversion at 840 nm (Charlie Chu @ Tecstar). We have also examined alternatives such as using amorphous silicon cells to reduce cost and the possibility of doing at least part of the program using direct solar power to reduce the dependence on the laser power beaming. Both of these alternatives have value but we see them as fallback positions.

<u>Health issues</u>

In this day and age, health and safety issues are paramount. Unsafe activities will no longer be tolerated. Knowing this we have implemented work to study the health issues associated with the space elevator.

One issue brought up is the possibility of discharging the ionosphere. Our calculations based on the size and conductivity of the ribbon and the electrical properties exhibited in our upper atmosphere illustrate that a small area (square meters) around the ribbon could become discharged in the worst conditions. The magnitude of this discharging makes us believe with high confidence that no adverse local or global phenomenon will occur. It also shows that it is unlikely, without considerable effort, that any kind of usable power may be generated by this same method.

A second health concern is on the use of carbon nanotubes. With any new material there is a question of whether it will cause biological damage when inhaled or ingested. To answer this question we have begun a set of studies to find out what might happen if raw carbon nanotubes or carbon nanotube composites got into a biological system. This would be a concern both during production of carbon nanotube composites and in the event of the ribbon catastrophically returning to Earth.

The initial tests conducted by Dr. Russell Potter at Owens-Corning found that carbon nanotubes do not disintegrate in lung fluid. This is to be expected due to the nature of nanotubes. It implies that if carbon nanotubes get into the lungs that it could remain there for a long time.

The next question is how well carbon nanotubes and carbon nanotube composites are inhaled or ingested and do they cause any damage in these cases. Dr. Brain at Harvard is currently conducting tests on mice to learn more about this. His initial results are expected soon. Initial results on prior rabbit studies reported by Foster-Miller also showed no adverse effects from carbon nanotube ingestion.

Damage in a biological system results when a material is: 1) inhaled, 2) not re-exhaled, 3) remains in the organism for a long period of time, and 4) creates damage to the organism while inside. Our initial results for carbon nanotubes demonstrated that number three is true. Number one is clearly true. Number two and four need further study. Due to the small size of carbon nanotubes it is possible that they will be exhaled like any other single molecule and not remain in the lungs and that because of their small size they may cause no real damage. These are the questions that still need to be answered.

The studies to date have been on raw carbon nanotubes which could cause a health risk during production of the ribbon but unlikely to occur in the event of a ribbon re-entry. Once in composite form the fibers will be too large to realistically inhale or ingest. Even after re-entry a very large percentage of the ribbon will be in pieces many centimeters to kilometers in length. Further studies and proper designs will be required to insure public safety in this area.

<u>Weather</u>

After initial discussions with the hurricane-tracking center in Pearl Harbor and James Arnold at MSFC we secured numerous satellite images on the global weather. We acquired global maps on lightning activity (see our book) and global hurricane tracks. In addition, visible, UV, and infrared satellite images were obtained for the last few years to examine the cloud cover in various regions. Based on this information we were able to make a first cut selection for an anchor location in the eastern equatorial Pacific.

In the next step we learned about a current program called EPIC. It is a five-year effort to study the weather at the exact location of our proposed anchor. The study will examine the wind, storms, waves, and clouds for this region with both ground and satellite resources and then produce a model to help predict the weather in advance in this region. We have contacted Bob

Weller from Woods Hole Oceanographic Institute about the EPIC study. He sent us a report covering this region called the Pan American Climate Study (PACS) study. The PACS study contains information on the cloudiness and wind velocity, among other information, for extended periods at our anchor location.

The PACS data is in one-minute intervals for 18 months at a location of 125°W, 3°S. With this data we have analyzed the steady-state and gust speeds of the wind. Gusts up to 15.5 m/s were observed. Our calculations show that the cable should survive wind speeds up to 72 m/s. We have also analyzed the PACS data for the amount of sunlight incident on the observing buoy. This data has some ambiguity in what the data means (clouds are not binary, they refract as well as stop sunlight) but some information is there. Where the curve matches an ideal sine curve we can assume that there are few clouds and where there is serious reduction in the light level there is complete blockage. We found that roughly 82% of the time the light level is above 67% of expected. Converting this into laser power beaming time is our next challenge but it appears that several power beaming platforms and active weather avoidance may be called for.

Independently, during their study for an anchor station, our colleagues at Anderson Associates found information on the wind and waves in the region. Their opinion on the weather as it relates to the anchor platform was:

> *"It is gratifying to see that the significant wave heights in the region do not exceed 3m and the wind speed 10 m/s (19.4 knots) for 95% of the time. These are substantially lower than the normal design conditions for semi-submersible platforms and for the large semi-submersible platform envisaged. In these weather conditions motions and accelerations will be minimal."*

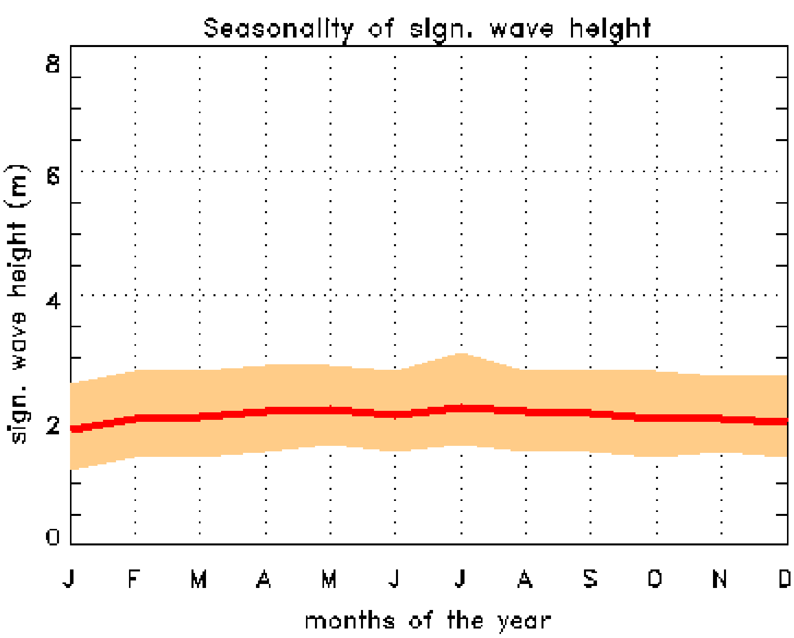


Figure 3: Significant wave heights for the equatorial region 1000 miles west of the Galapagos Islands

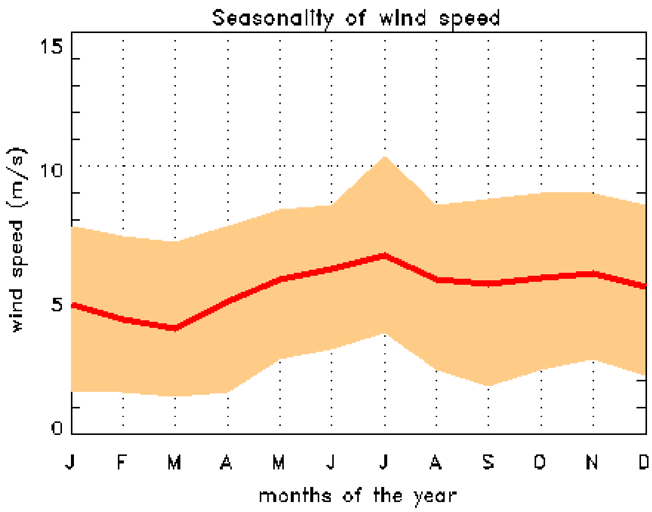


Figure 4: Wind speed data for the region 1000 miles west of the Galapagos Islands

Ribbon Dynamics

The dynamics of the elevator, in general, are fairly straightforward but to ensure proper operation we need to examine the details of the elevator dynamics.

In 1975, Jerome Pearson published a technical article that included the a discussion on the natural frequency of the space elevator. Pearson found that the natural frequency depended on the taper ratio of the cable and in some cases would be near the critical 12 and 24 hour periods that could be problematic. Pearson also stated an ugly equation for calculating the shape of the cable as a function of the material strength, planetary mass, and planetary rotation speed.

We have taken Pearson's original equation and attempted to simplify it into a more usable and intuitive form. However, this equation does not simplify well and like Pearson we have resorted to an analytical solution. In our case, however, we have ready access to spreadsheets that easily handle these types of calculations. We have composed a set of spreadsheets that produce ribbon profiles, tension levels, linear velocities, counterweight mass and total system mass. This spreadsheet is designed to handle different planetary bodies, rotation rates and applications.

Another spreadsheet we have composed is similar but for elevators with their anchors located off the equator. In this case the ribbon is found to sag toward the equatorial plane but remain entirely on the side as the anchor. This sag in the ribbon is due to the non-axial pull of gravity on the ribbon. The magnitude of the sag depends on the planetary rotation, planetary gravity and mass to tension ratio of the ribbon. In the case of a Martian cable, where anchoring the cable off the equator would allow it to avoid the moons this calculation is critically important. In the Martian case the cable extends parallel to the equatorial plane with only a 3 km sag back toward the equatorial plane when the cable is moved 900 km from the equator. This simple reanchoring of the cable would allow us to avoid any difficulties with the Martian moons.

What these and the dynamics work discussed below imply is that from a system stability and operations it is possible to move the anchor tens of degrees off of the equator if other factors (weather) permit.

In addition to the spreadsheets that we have assembled, David Lang has conducted computer simulations on the dynamics of the system. The code Lang is using was originally designed for modeling the ProSEDs experiment. Lang has modified it to examine the elevator scenario. Thee results form these simulations show that the elevator is dynamically stable for a large range of perturbations. The natural frequencies were found to be 7 hours for in-plane (orbital plane) oscillations and 24 hours for out-of-plan oscillations. The out-of-plane number is misleading however. For any elevator or geosynchronous satellite a 24 hour period is found for the out-of-plane because that simply implies an inclined orbit. For determining the stability, Lang gave the system various angular deviations, initial velocities and also quickly reeled in some length of the ribbon at the anchor. At some limit in each of these cases the elevator becomes unstable. What was found was that angles of tens of degrees were required to create a catastrophic failure. (The energy required to move the counterweight this far is equivalent to that required to lift 3000 loaded semi trailers kilometers into the air.) It was also found that reeling in 3000 km of ribbon in 6 hours will create a catastrophic failure. Each of these perturbations is well beyond any we expect to encounter. The events leading up to any of these are easily avoidable.

Lang also suggested that we consider a pulse type of movement for avoidance of orbital objects rather than a translational as we have been proposing. The difference is that in the pulse situation the anchor station is moved one kilometer and moved back to its starting position. This will send a wave up the ribbon to avoid an orbital object. The pulse will reflect off the counterweight and return to the anchor where an inverse pulse maneuver is conducted to eliminate the pulse. The result is a quiet system. In our proposal the anchor would be moved and remain there. This would send a long pulse that could oscillate up and down the ribbon for some time. Simultaneous pulses and a complex movement of the ribbon would result. This is a simplified explanation of a complex operation and response but the point is that there are operations that still need optimization.

Along with the computer simulations we have conducted some hardware tests of various ribbon designs and damage scenarios. The tests included several sets of ribbons with parallel and diagonal fibers composed of plastic fibers and epoxies or tape sandwiches. The ribbons ranged from two to four feet in length and were placed under high tension loads.

In the ribbon tests we found much of what was expected and predicted by our models. In situations where there is continuous rigid connection between adjacent axial fibers, aligned or diagonal, high stress points are created at the edges of the damaged area. These high stress points tend to be the starting point for zipper type tears and greatly reduce the optimal strength of the ribbon. On the contrary, ribbons with non-rigid interconnects between fibers had minimal stress points and yielded at high tensions and larger damage. A full description of the optimal ribbon design is found in our book. Similar tests are now being arranged at Rutgers to explore the degradation that might occur. We have also started to set up ribbons close to what will most likely be the final design.

Design studies

The real heart of this program's technical work involves design studies of a long list of components and how they work together. Most of the work is covered in the book we have published, *The Space Elevator*. However, during the last couple months of our NIAC Phase II all of the technical material could not be placed into the book prior to publication. Below we will cover a lot of the newer work and design modifications that have evolved.

Anchor

We have based much of our anchor station work on the *Sealaunch* program which uses a refurbished floating oil drilling platform. This was done because that platform is very close to what we need, is in operation in a similar fashion and location to what we need and is easy to point to. Essentially it is a good example to illustrate that the platform we need can be built. What we have found is that there are more optimal platforms for our purpose. In fact, it appears that we can get pretty much an ideal platform for our application custom-built on fairly short notice and at a reasonable price.

Art Anderson Associates out of Bremerton, Washington, has built and refurbished large ships for decades. They have extensive experience in ships the size of aircraft carriers and have examined our needs. Our constraints include the required platform size operational scenarios, the maintenance plan and stability requirements. The specific requirements included:

- The anchor platform will need to be operational continuously for years.
- The size of the power beaming platforms will be constrained by the required length of the current laser system (150 m).
- The stability of the power beaming platform is set to be roll and pitch of a few degrees maximum and the maximum angular velocity must be less that about 10 degrees per minute.
- Twenty megawatts of power on the power beaming stations
- One km/day of movement capability with 100 m position accuracy.
- All platforms must be self-propelled and capable of going to a drydock.
- Living facilities for 100 staff and families.

Some of these requirements force other design requirements. The continuous operation for example forces the anchor platform to be able to move the ribbon anchor from one platform to another at sea since no single platform can remain operational indefinitely. The large size of the power beaming platforms will require custom drydocks.

It was found that large floating platforms have been studied and designed (Bechtel National Inc.) that meet all of our requirements for our anchor location. It was also found that such a vessel can be built at several facilities around the world, one is Hyundai in Korea. The cost of the custom built platforms are only slightly more than the quoted cost of a refurbished system and would have much better performance and expected lower maintenance.

The study conducted by Art Anderson associates also pointed out several additional issues to consider such as the location of the drydocks, how to finance the drydocks, maintenance schedule, transportation from construction facility to anchor, airstrip possibilities, etc.

Figure 5: Mobile Offshore Base by Bechtel National Inc.

Climber

The climbers are simple in concept but need to meet a number of critical performance criteria. The performance of the climbers affects the construction schedule and thus the risk of failure. The climbers also define the overall performance of the space elevator. Because of these facts we have conducted several studies on the design of the climbers to ensure the optimal performance.

Based on the original design we constructed simple mock-ups of the climber and examined possible problems and required modifications. All of the design numbers (masses, power, build-up schedule, components, overall design,…) were re-examined as part of the process.

One of the design modifications that was implemented was to increase the drive system preferentially as the climber mass increased. This is possible because specific components such as the power receiver array, structure, and control systems do not increase linearly as the overall size of the climber increases. The mass of these components increase more slowly than linear and the extra mass available can be dedicated to a more powerful drive system. In examining the numbers we found that the drive system could increase by a factor of two and the travel time to the 0.1 g altitude (the point when the next climber could be placed on the ribbon) would drop proportionately. This will reduce the construction time and the overall risk of building the system.

We have also considered a number of alternative designs to adding ribbons to the initial ribbon. These have included: 1) leaving the spool on the ground and taking up only the end and then sending up a second climber to attach the second ribbon, 2) grabbing the ribbon in the middle and taking it up then attaching it, 3) leaving the spool on the ground and attaching the ribbon as the climber ascends with the ribbon being fed up to the climber, and 4) variations and hybrids of these. What we have found is that there are a number of constraints on the system that limit what can be done. The primary factors that limit the ribbon build-up are: 1) the requirement for the ribbon to have a taper with the narrow end down, and 2) the lifetime of a small ribbon can be hours to days if not attached to the main ribbon. These factors have forced us to remain with our original design.

The traction drive system of the climber is critical and we have examined the possible problems we will encounter in this area. We have discussed the situation Goodyear, Michelin, and Bridgestone and examined several of their track systems. It appears that the development to date in this area is at the level where these commercial entities can produce the tread system that we need. One of the most critical items that needs to be addressed is the wear and tear that the tread system will induce on the ribbon.

The major design considerations include: 1) any bending of the ribbon such as around rollers will induce wear, 2) since the ribbon is elastic it will contract as it passes through the climber, 3) any slippage on the individual fibers will cause wear and 4) the contraction of the ribbon and its size changes as the climber ascends. The contraction of the ribbon will be as much as 10% of the length of the tread. In general operation it will be closer to 3% at the anchor and decreases as the climber ascends. Even 3% is substantial over a 2 meter long tread: 6 cm. Our analysis of the tread system shows that it is a challenging engineering problem but not unsolvable. The design may require multiple smaller treads and a "soft" hold on the ribbon to allow for changes. The final solution will require extensive testing and iteration to ensure proper construction.

We have also reworked the masses of the climber components. The masses in general are very close to our original numbers which indicate that they are probably close to what will be found in the final, fully-engineered system. The new design includes an offset photo array that is not pierced by the ribbon, a lightweight structure and balanced design.

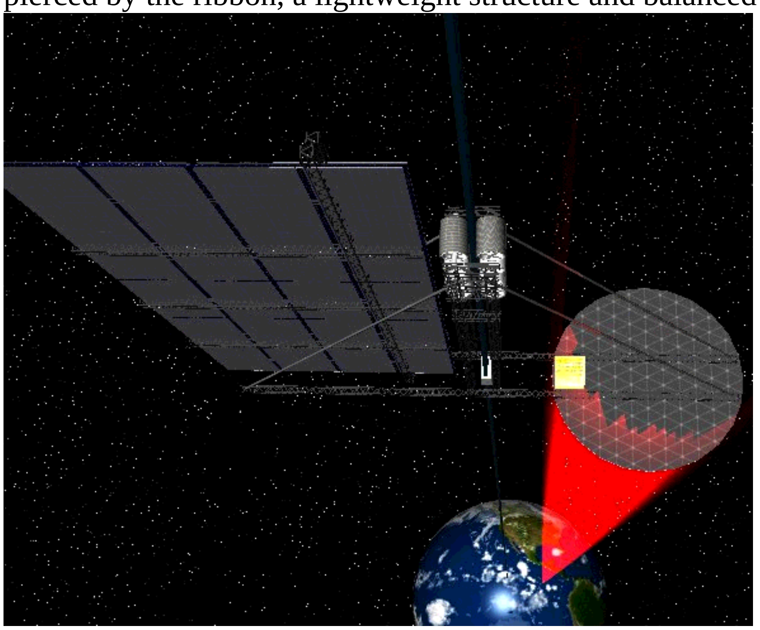


Figure 6: Climber design showing offset photocell power receiver, electronics, tread roller system, structures and payload (large solar panel on left).

In discussions with Joe Carroll, Tether Applications Inc., we examined one additional problem that may arise. Photocells on arrays are strung together to generate higher voltages and then in parallel to increase the current. If any cell in a string is not illuminated the entire string is effectively turned off and generates not power. Since we are not using a constant, wide-field light source such as the sun, any misalignment in our laser would reduce the light on one part of the array. In the case of misalignment if the photocell strings are not arranged properly the entire string could be turned off and result in the entire array shutting down. We have produced an arrangement of strings in hexagons that would limit the loss in power due to any misalignment. This is a more minor aspect of the overall space elevator design but illustrates the level of detailed engineering that is being done and still needs to be done on this systems.

Ribbon infall

A major question on the space elevator or any transportation system is safety. For the initial proposed system where humans will not be the early cargo the primary concern is the damage due to a falling ribbon. We have studied this possibility, obtained information on global wind patterns, possible ingestion methods and the possible population areas affected if a cable were to come down. This work is in general terms but we hope to fill in the details quantitatively in the future. We are working with Owens-Corning and Harvard on this. The raw numbers suggest that the worst case cable infall is not as bad as the best case, nominal operation of current rocket programs.

Ribbon

The ribbon is the key component of the space elevator and technically the most challenging. We have spent substantial effort on the carbon nanotube composites required for production of the ribbon and in studying the ribbon design.

Initially, we had proposed a sheet-like structure for the ribbon. As our knowledge of composite production, degradation methods, and available materials increased we were able to produce and test a much more robust ribbon design. The current ribbon design consists of thousands of individual fibers aligned parallel with interconnecting tape sandwiches spaced 10’s of centimeters to meters apart (design discussed in *The Space Elevator*). This design has very positive degradation characteristics as damage is incurred. Short lengths of ribbon made have been tested and these characteristics demonstrated. 3M corp. has been a prime contributor to this effort in supplying information and supplies for the interconnects. The interconnect questions that remain involve long-term creep of the system and employing all of the required characteristics in a single tape structure. In discussions with 3M this looks viable.

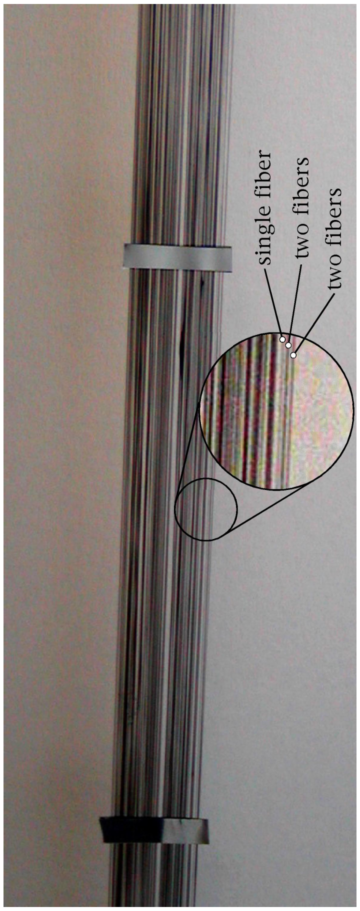


Figure 7: A section of a 60 cm long, 1 cm wide carbon nanotube composite fiber ribbon with two tape sandwich interconnects shown. The current strength of the carbon nanotube composite fibers is comparable to steel with 3-5% loading of nanotubes. To build the elevator we will need strengths of 30 times steel.

We have received carbon nanotube composites from both University of Kentucky and Foster-Miller Inc. We have used some of the fibers to make a ribbon mock-up and sent some of the composites to LANL for metal coating and testing in an atomic oxygen chamber. These tests are not complete yet but should be shortly.

One possible alternative ribbon design could implement well-developed weaving techniques such as the Leno weave. We have examined this possibility and believe it warrants further investigation.

We have also examined various splicing techniques for the build-up phase of the space elevator. Some of the techniques have included epoxy connections, tape sandwich connectors, with and without additional temporary supports, UV curing, etc. The optimal design is the same technique as the ribbon is constructed with: tape sandwiches placed at specific spacing. We have also examined the spacing of the interconnects to insure minimal mass and optimal attachment as tape interconnects are placed overlapping some number of previously added ribbons.

One other recent development is the understanding of atomic oxygen degradation of the fibers. It is believed that the carbon nanotubes are resistant to erosion by atomic oxygen based on LDEF studies. If this is the case, we are testing this now, then we would expect to see the matrix to be preferentially etched on the fibers and the carbon nanotubes be exposed. Eventually the entire surface of the fiber will be exposed nantubes and the erosion of the matrix will cease. This limiting process is similar to what happens to many metals as they oxidize and appeared to have occurred on several composite samples from LDEF. If we demonstrate this hypothesis then the fear of damage due to atomic oxygen would be greatly reduced.

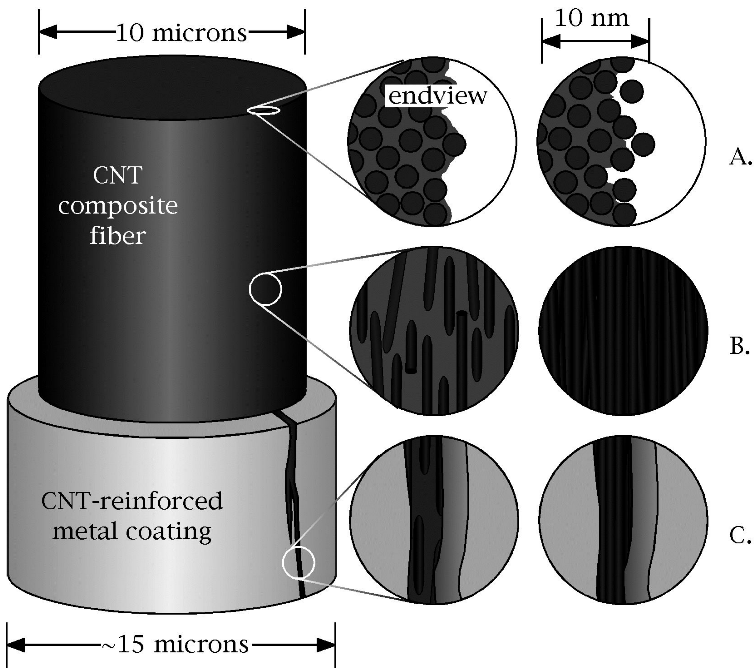


Figure 8: Atomic oxygen damage illustrated. The left-hand column is prior to exposure to atomic oxygen. The right-hand column is after exposure at or above a limit.

Propulsion

One of the major components that impacts the construction, risk, cost, schedule, and complexity of the space elevator is the propulsion system on the deployment spacecraft. The reason this single component has such a dramatic effect on the program is because it can be the largest mass component that needs to be deployed on conventional rockets and thus limits the initial ribbon size that can be deployed from space. A reduction in the initial ribbon size ripples throughout the system and impacts everything else.

With this in mind we have worked hard to understand and reduce the size and risks associated with the propulsion system. Initially, we had proposed a very conventional chemical rocket system of liquid and solid engines. This system was very massive and required some complex maneuvers on-orbit. It was viable but obviously a system driver. An alternative to chemical systems that has been around for decades but only used in limited numbers is electric propulsion in various forms.

Part of our effort was to examine the possibility of using a form of electric propulsion for our deployment spacecraft. We examined various reports on moving large payloads with electric propulsion and eventually found out about efforts at Princeton, JPL and Russia studying a magnetoplasmadynamic (MPD) thruster. The MPD is the largest and most efficient of the electric propulsion method. A 200kW system, near the size we need, has been built and tested. After 500 hours of operation no visible signs of degradation were observed. MPD’s have also flown on two Japanese missions. According to Edgar Choueiri at Princeton he could build the propulsion system with little effort or cost ($100k). The question he has is on the power supply.

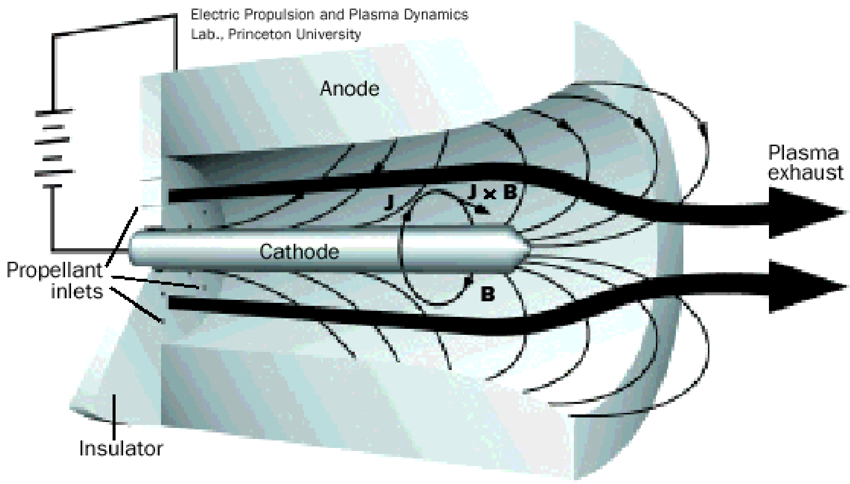


Figure 9: An MPD propulsion system. October 2000 Industrial Physicist

To supply the 800kW that our optimal MPD system would require we have found that we have the solution already in the form of our laser power beaming system. The difficulty in this arrangement is to design the laser power beaming to track an orbiting spacecraft. Initially the spacecraft will be in a low-Earth orbit and only be in sight of any power beaming system for a few minutes. To get a reasonable duty cycle to raise the orbit we will need all of the laser power beaming systems that we are planning for our climbers to be online from the beginning. As the orbit is raised by the MPD the duty cycle increases and the process becomes more efficient. We have found that depending on the exact arrangement increasing the orbit from LEO to GEO could take as long as a year. With a modification and use of a small solid rocket engine we can reduce the LEO stage on reduce the orbital change timeline to 150 days.

As a result of the improved propulsion system we will be able to reduce the number of large rockets required from eight to four and double the size of the initial ribbon. This will dramatically reduce the complexity, cost and risk of constructing the system. In addition, we have redesigned the spacecraft to have two separate solar arrays on opposite sides of the main craft with one tilted forward along the orbital velocity and one backward. The reason for this is to improve the energy delivery during the orbital change. As the spacecraft moves from the horizon to nadir in its orbit one array will be more normal to the laser beaming system and will be used. As the spacecraft moves from nadir to the horizon the other array will be more normal and be used.

Orbital objects

Orbital objects have always been a concern. We calculated that a large orbital object, satellite or debris, would strike the space elevator at least once a year if nothing were done to prevent it. This problem is currently of concern because our legal study has stated that we will not be allowed to construct the space elevator unless we can demonstrate that it will not get in the way of existing, operational satellites. In addition, the recent cancellation of the ProSEDS mission five weeks prior to launch because the possibility that it might strike the ISS demonstrates the reality of the concern.

We have gone through a complete calculation on the likelihood of an orbital collision and found tracking systems that can warn us of an impact days to week ahead of time and a system for moving the ribbon to avoid the collision. The tracking system would consist of various radar and optical detector systems such as have been proposed and implemented for different applications. The design of the Allen Array, a phased array radar system using many small dishes, is one possible design that we are considering. The optical detectors proposed by Ho (LANL) is another system for completing the detection of small objects.

Viking Scientific who works with JSC on orbital debris has offered to help with this work and attended our conference.

Market

For any system to be realistically considered for construction it must be clearly demonstrated that it has a value. In our case the initial market that we would be addressing is the launch of satellites from military to telecommunications to scientific probes. The current launch market is having economic difficulties but with reduced launch costs it has been predicted that the market would grow rapidly and below the $1000 per pound market rise dramatically.

There have also been a number of other factors determined that will affect acceptance of a launch system and how it will fair in the current or future market. Some these are the reliability of the system which is only accepted after many launches and another of the performance characteristics (vibrations, envelop size, …). Examining the document produced by a colleague at Lockheed Martin we find that the space elevator holds a very positive position over alternative launch systems from both cost and performance standpoints.

The immediate market size expected when the space elevator is ready to launch its first commercial payload is around two to three billion dollars per year and expected to grow rapidly as system operations improve.

Cost

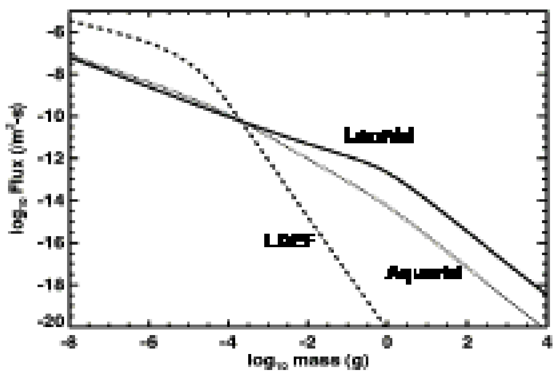
We have continued to check the cost of constructing and operating the space elevator. Separate independent cost analysis is underway to improve our numbers. Most of the component costs can be estimated fairly well. Integration can also be done. The biggest cost uncertainty comes from the non-technical costs. The technical costs of the space elevator will be around $6.5B ± $0.5B however the non-technical costs could easily be much greater than this depending on how the program is run. Such high program costs have appeared repeatedly in the past.

Checking data

With our conference, numerous collaborators and interested technical people we have received both direct and general review of our calculations. Some of these have been extensive, completely independent checks on our mass and deployment calculations and others have been more simple or specific examining atomic oxygen erosion, meteor and debris impacts, CNT composites, etc. while others are more general overall concept reviews like our conference. These various types of reviews have helped to refine our design and specific numbers but none of them have found a fatal flaw in our system. This is encouraging and we will continue these independent reviews.

Leonid Meteor Shower

The Leonids are a trail of dust and debris left by the Tempel-Tuttle comet as it traverses our solar system each 33 years. The last passage was in 1998 and the next is expected in 2031. The dust and debris left by the comet passage disperses and leaves the neighborhood of Earth on a timescale of years though some debris always remains. The flux density of the debris can fluctuate by 10,000 from year to year. The Leonid debris also has a distribution of debris that includes dust particles and objects up to 10 cm in diameter.



An article published by McNeil, Lai and Murad, *Charge Production due to Leonid Meteor Shower Impact on Spacecraft Surfaces,* discusses the impact probability on spacecraft and the details of the Leonid debris. The flux density from McNeil is shown in figure 1. This flux density is for a Leonid shower with a peak visual flux of 1000 meteors per hour. The standard peak is 10 to 20 and the largest in 1966 was 160,000. We can calculate the probability of impact on the elevator ribbon based on the 1000 peak number and then scale from there.

Objects larger than about 10 cm have a finite possibility of destroying the ribbon. Objects as large as 5 cm in diameter has a small chance of destroying the ribbon. If we consider a weighted probability function we might approximate the likelihood of destruction with the likelihood of impact by a 10 cm or larger object. In our baseline, with densities of 3 gm/cm^3 (estimate for the Leonid debris), this relates roughly to a mass of about 1500 gm (4/3*3.141*5^3*3) or a flux density of 10^{-17}/m^2 s. A typical Leonid shower lasts roughly 2 hours or 7200 s and the total area of the proposed elevator ribbon is 10^8m^2. For a Leonid shower impinging orthogonally on the ribbon face (worst case) we get a probability of damage leading to destruction for each annual passage through the Leonid debris of roughly 1/100,000 for the showers with peak visual rates of 1000/hour. For a more standard shower the probability would be 50 to 100 times less. For the largest likely event (possibly in 2031) the probability would go up by 160 to a 1/625 possibility of severe damage. These are rough estimates and more accurate calculations are required. However, these estimates indicate that until 2031 the danger is probably minimal even without modification to the system. By 2031, modifications and mitigation techniques could be implemented to improve survivability such as locating the ribbons temporarily edge on to the shower or moved to be shadowed by the Earth.

Legal Issues

As our efforts progressed various questions arose on issues that were not technical but related directly to the viability of constructing a space elevator. One area of concern that came up was legal.

Since our team has limited legal experience we commissioned The National Remote Sensing and Space Law Center at The University of Mississippi to investigate the possible hurdles that construction of the space elevator would encounter. The study looked at both national and international legal and policy issues. Professor Joanne Gabrynowicz led the investigation. The breakdown for the report was:

International Air and Space Law Issues

1. The Outer Space Treaty: Four possible issues
2. The Liability Convention: Two Possible issues
3. Delimination: One possible issue
4. The Chicago Convention: One possible issue

International Maritime Law Issues

1. The Law of the Sea Convention: One possible issue

U.S. Licensing and Regulatory Issues

Jurisdiction and Authority Overview

1. DOT/FAA/AST: Five possible issues
2. DOS: One possible issue
3. DOD/DOE: One possible issue
4. FCC: One possible issue
5. NASA: One possible issue
6. EPA: One possible issue
7. Coast Guard/Local Ports: One possible issue

The twenty issues examined ranged from very specific to very broad and covered all aspects of the construction and operation of the space elevator. None of the issues found were definitive show-stoppers, each has a viable solution though most if not all will required work and possibly legal activity to settle.

To begin the process we have met with the FAA, FCC, NASA and components of DOE and DOD. At each we were received well and were thanked for bringing the various agencies in on the process at an early stage.

Major issues that will need concentrated effort include:

- Due to the legal right-of-way of existing satellites, the space elevator will be required to avoid collisions with on-orbit satellites. This issue must be settled prior to construction by a clear demonstration that the elevator can eliminate the risk of collision. This matches the technical requirement to avoid collisions and we feel that it can be achieved technically but legal proof may require additional work.

- Since the space elevator will go through geosynchronous altitude it must be able to obtain the orbital position slots needed for operation. This may be solved in one of several ways. First, the elevator will likely be displaced several degrees south of the equator and thus not be in the assigned orbital slot for geosynchronous satellites. Second, it may be possible to purchase the required slots as they become available.
- If the space elevator can not find liability insurance it may not be allowed to be built. We met with Aon Insurance about coverage for the space elevator and payloads launched from the system and found them very receptive. From the first meeting it appears that insurance can be found to cover the liability on the space elevator.

Applications of the Space Elevator

Every development must have some value to be worth doing. In the case of the space elevator there are both short and long-term applications. However, since we started this effort with little prior technical literature on the uses and applications of the space elevator we needed to define the applications and limits to insure that our development was properly directed.

The immediate first use of the space elevator is deployment of Earth-orbiting satellites for telecommunications, military, Earth monitoring, etc. These satellites are placed in low-Earth orbit and geosynchronous Earth orbit both equatorial and inclined. It is clear that the space elevator will work well for deploying equatorial geosynchronous satellites. To do this the satellite simply needs to be set adrift at the proper altitude, nothing needs to be done. For inclined geosynchronous orbits delta-V's required are equivalent to the orbital velocity times the sine plus (1 - cosine) of the inclination. This required propulsion is much less than what is required to place the satellite into this orbit starting from Earth with a rocket.

For low-Earth orbits we have a separate problem. At low-Earth orbit altitude on the space elevator the satellite will not have the required orbital velocity so it can not be simply let off at the proper altitude. To enter an equatorial low-Earth orbit the satellite would be taken to an altitude above 23,500 km and dropped into a highly elliptical orbit and then circularized using a tether of small propulsion system. To enter an inclined low-Earth orbit it is the same scenario as for the inclined geosynchronous orbit discussed above with the propulsion event occurring at the highest altitude (immediately upon release) along with the circularization.

Earth orbit applications from satellites to manned operations are clear and dramatic cost savings are evident (up to 99% savings). For the longer-term, we also considered applications beyond Earth orbit. We produced calculations on the mass and length of cables on various solar system bodies. This was an initial calculation that left out third-body effects or other environmental factors. These initial calculations showed both common perceptions (Mars requires a small cable and the Moon a large one due to rotation rates) and came up with a few other interesting details. Small, rotating bodies such as asteroids and some moons of Jupiter and Saturn require the smallest cables and could allow for the best entering point to these systems. However, the ribbon length is more determined by the rotation speed and use (arrival and launch velocities required) than the size of the body. Venus along with the moon require extremely long cables.

The traditional markets the space elevator will address include:

- Telecommunications
- Remote sensing
- Department of Defense

The U.S. satellite launch market is expected to be at 110 launches per year when we enter the market[1].

However, we plan to extend this traditional base and target smaller institutions who are interested in space activities; clients who, until now, have been unable to afford it. The new markets we will encourage and target include:

- Solar Energy Satellites (clean, limitless power from space)
- Space-System Test-Bed (universities, aerospace)
- Environmental Assessment (pollution, global change)
- Agricultural Assessment (crop analysis, forestry)
- Private Communications Systems (corporate)
- National Systems (developing countries)
- Medical Therapy (aging, physical handicaps, chronic pain)
- Entertainment / Advertising (sponsorships, remote video adventures)
- Space Manufacturing (biomedical, crystal, electronics)
- Asteroid Detection (global security)
- Basic Research (biomedical, commercial production, university programs)
- Private Tracking Systems (Earth transportation inventory, surveillance)
- Space Debris Removal (International environmental)
- Exploratory Mining Claims (robotic extraction)
- Tourism / Communities (hotels, vacations, medical convalescence)[1]

We expect solar power satellites to be one of the major markets to develop when we become operational and have begun dialogs with BP Solar about launch requirements and interest. Solar power satellites consist of square miles of solar arrays that collect solar power and then beam the power back to Earth for terrestrial consumption. Megawatt systems will have masses of several thousand tons[2] and will provide power at competitive rates to fossil fuels, without pollution, if launch costs get below $500/lb to GEO.

Another market we expect to emerge is solar system exploration and development. Initially this would be unmanned but a manned segment, based on the Mars Direct (Zubrin) scenario, could emerge early after elevator operations begin. The exploration market would include:

- Exploratory and mining claims missions to asteroids, Mars, Moon and Venus.
- Science-based, university and private sponsored missions.
- In-situ resource production on Mars, and Moon.
- Large mapping probes for Mars and the asteroids.
- Near-Earth object catastrophic impact studies from space.

[1] Zogby International
[2] NASA and ESA studies

The exploration market would be expected to consist of only a few lifts a year within two years of operations but each mission would be a larger one and produce substantial media attention. In the long-term, such practices will increase our revenue as manned activities in space grow.

Another market to consider in the coming decades is space tourism. We may encourage tourism early on with day-long joyrides to space and later possibly lease a ribbon for long-term, hotels in space. Such activities will produce positive public perception and broaden the long-term market. In a recent survey by Zogby International it was found that " 7% of affluent(people) would pay $20 million for 2-week orbital flight; 19% would pay $100,000 for 15-minute sub-orbital flight". These numbers indicate a possible future market that could be tapped as well.

One exciting possibility that becomes reasonable with the Earth space elevator is colonization of Mars in the near future. To really accomplish this would take several fully operational space elevators on Earth and an investment in a Martian elevator. We have produced an initial Mars elevator design which includes: 1) a power beaming system using L'Garde's inflatable solar concentrators, 2) a deployment scenario minimizing the propulsion requirements, 3) an overall system with modules on each end of the ribbon, 4) a self anchoring module on the lower end of the ribbon, 5) a power beaming, propulsion, and capture system at the upper, and 6) an anchor location on Olympus Mons to avoid both the moons and the dust storms. Much of the sizing requirements sizing requirements were loosely based on Zubin's work.

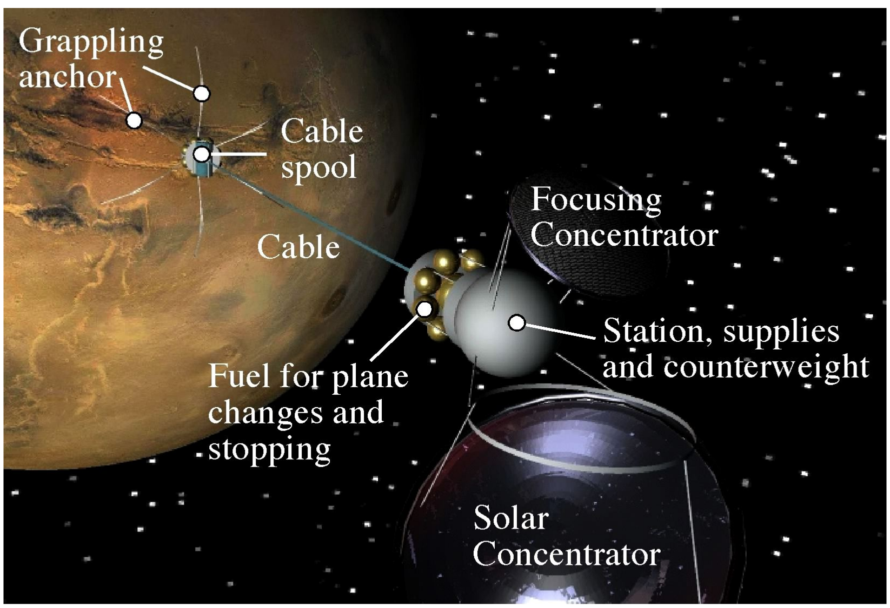


Figure 10: An illustration of a Martian Elevator

As is obvious in our discussion on the colonization of Mars, the elevator concept allows for entirely new modes of design that are not realistic with rocket systems. One application where this is clearly an advantage is in the construction of space stations or habitats in space. Without fairing restrictions entirely new station modules can be considered. One structure that is not generally considered feasible now but would be feasible with the space elevator is a geodesic sphere that is inflated prior to launch. Calculations show that a 30 m diameter sphere could be lifted to geosynchronous altitude and outfitted using the first space elevator. It would require a minimum of two climber loads (one carrying the sphere, some air and internal structures and a second carrying the primarily air) and more likely five or six launches to outfit an operational station capable of supporting tens of individuals initially and up to 100 individuals on a long-term basis. These calculations are based on discussions with L'Guard, a leader in space inflatables. According to L'Guarde such a structure is completely viable with current technology if the inflatable structure is not required to fold up to fit into a fairing and then unfold on orbit.

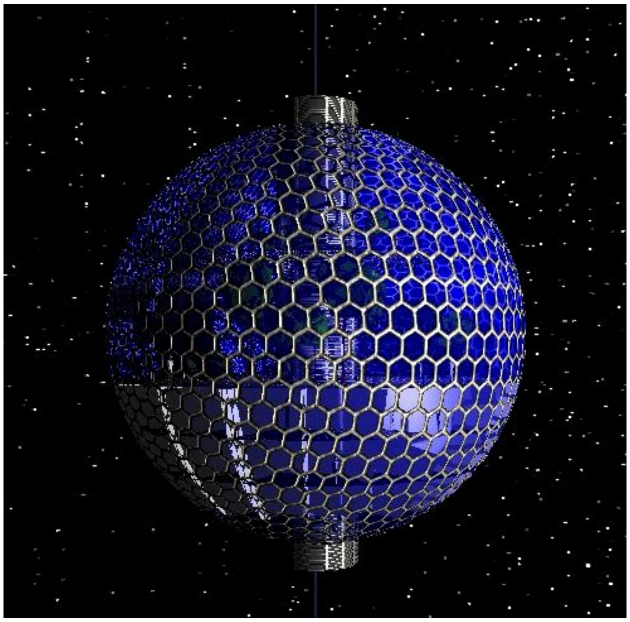


Figure 11: One conceptual idea for a space station. The basic structure is an inflatable sphere with geodesic supports. Thee internal volume would accommodate one hundred people and yet the mass would be low enough to be built quickly with the first elevator.

We have continued our pursuit of possible applications by examining elevators for use on small bodies such as rocky moons and asteroids. These turn out to be ideal applications. With minimal gravity and some rotation an elevator can be lightweight but long enough to have high tip velocity. The attachment to an asteroid is the primary difficulty but with the body and system sizes we are discussing a net or strap around the small body to hold onto it may work well. Asteroid-based systems could be viable with Spectran or Kevlar and not require the CNT composite development.

The various design aspects of an elevator on a small body must look at the travel times expected and the payloads being moved. In certain cases it is easy to make the mistake of building an elevator too small and moving large payloads too quickly. The result is insufficient time for angular momentum to be transferred from the planetary body to the climber and cargo. The worst case is an elevator that is pulled down and wrapped around the planetary body. To avoid this the counterweight and travel times must be designed based on the cargo size and not on the ribbon size.

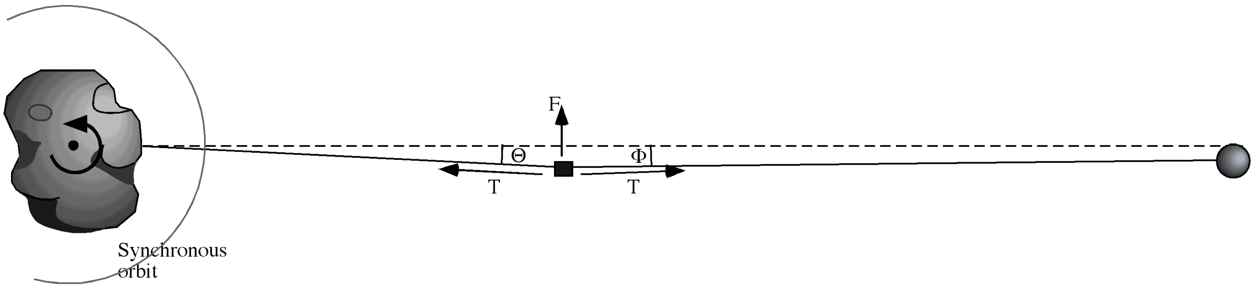
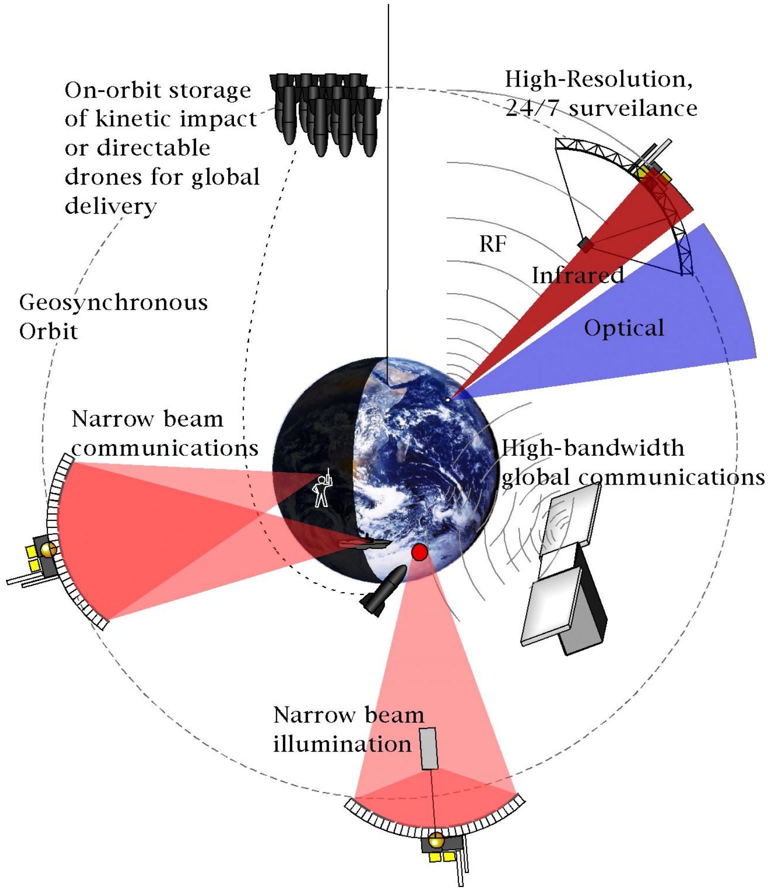


Figure12: The force diagram for a climber on a small-body elevator. In a poorly designed case the restoring force F will be insufficient to maintain the ribbon's angle from normal during fast climber transit.

A few of the military applications that a space elevator would enable include:

- High-resolution, broad-spectrum, 24/7 surveillance from GEO
- Narrow-band and pinpoint communications
- On-orbit storage of kinetic impact weapons or observation drones for fast global delivery
- Spotlight illumination
- Control of global communications

In general, the space elevator is not optimal for offensive weapons deployment due to its vulnerability and slow delivery time to orbit.



Investment and Future funding

Over the past three years we have investigated all of the technical details of the space elevator. In our opinion the major challenge to the construction of the space elevator no longer resides in the technical effort but the financial.

The space elevator program does not fit into the standard private financing models. The timescale for return on investment is fifteen years, considerably longer than conventional investors are interested in. The alternatives are private investors who are interested in investing to leave a legacy or public financing in terms of bonds or federal grants. We have investigated both.

On the public financing side:

- NRO BAA: Submitted two proposals, one each year, to develop the high-strength materials and ribbon. The funding was $350k.
- DARPA: We briefed DARPA and found interest there. They suggested we apply to their BAA announcement. We sent in a proposal to study the elevator but it was rejected. The funding was $118k.
- Space Launch Initiative: We have talked to various people at the SLI program at MSFC and NASA HQ. The SLI program is designed to look at advanced rocket technology. The SLI program has stated that it has no interest in funding alternative technologies.
- NASA: We found that there are a couple NASA AO's for tether work. These funding opportunities are for roughly $100k maximum, insufficient to move the program forward. We are on one of these proposals with Joe Carroll. We have also considered submitting an unsolicited proposal to NASA HQ, as suggested on the NASA website, however we were discouraged from doing this because the possibility of success was very low. We briefed NASA HQ directly and found this to be the case. NASA HQ was enthusiastic about the program and its potential but offered no avenue for acquiring funding.
- Air Force: We met with the Air Force Space Missile Command Center at the Los Angeles Air Force base to discuss our program and future funding. The meeting went weel though the SMC does not fund any development. They only purchase complete systems. Through the National Defense University we contacted the Deputy Assistant Secretary of the Air Force. They were interested and suggested we brief the Chief Technologist at AFRL. We briefed Barbara Wilson, Chief Technologist of AFRL, and received a very good review. However, no funding is available. The concern was that the CNT composite was not available yet though they were not willing to commit funds to this development.
- State Funding: We found state funding from California, Oklahoma, Nevada, Wisconsin, Hawaii, … This funding was in the form of workforce development matching funds and bonds for purchasing facilities. One additional possibility was a USDA low-interest, long-term loan. This funding generally requires prior equity or funding from another source. We have not taken advantage of this source of funding at this time.
- Congressional briefings: We have briefed congressmen and senators finding interest and stated support but this was in the form of working with us but not funding. Congressmen met included Dicks, Ensign, and Gibbons. Additional meetings are scheduled including a National Space Society sponsored lunch briefing of critical congressmen. We have also contacted roughly 20 congressmen by mail and telephone inclduing sending copies of our book. we have been invited to the Canadian consulate on September 12 to discuss how Canada can get involved. A contact in Singapore has suggested we talk with that government as well and has stated he has two people, one from Toyota, who are considering flying over to discuss the program.
- Foreign interest: The Canadian Space Agency has invited us to brief them and would like to collaborate on future work. The Canadian government has offered us attractive tax breaks, incentives, matching funds and assistance for any work we conduct in Canada. These incentives amount to getting $2.50 of work for every $0.62 we spend. The European Space Agency has put some funds into investigating how they can participate, expressed interest in us relocating to Vienna, and will be inviting Dr. Edwards over to

brief them in the near future. The Australian media has been covering our work and we have been presented to members of the Australian parliament. Possibilities have also been expressed from Singapore and Japan.

On the private side:

- Venture capitalists: the program has been discussed with several venture and angel investors. The general consensus is that the program is very exciting and interesting and the timescale is too long for their interest. They have suggested that the best route is to acquire additional federal funds first.
- Individual investors: we have had several discussions with individual investors who have expressed an interest in investing in the space elevator development. These funds are generally insufficient for the program to move the program to move forward. Larger investors are possible but are extremely difficult to get in front of.
- Direct Public Offering: It has been suggested that we capitalize on the high public interest in this program by issuing stock and selling it to individuals. It is conceivable that this would raise some initial capital but is unlikely to raise all of the funding needed for the entire program. However, by issuing stock at this extremely early stage the endeavor would be marked as less than reputable by professional investors and may violate SEC regulations.

The program has attracted a lot of attention and we have been able to address many of the financing issues. The bottom line is that financing is difficult for this program and sufficient financing, if available, could take up to 18 months to acquire. The larger, accredited, private investors appear to be the most viable method of initial funding at this point. Federal funding is a possibility but we believe it will require a major congressional initiative.

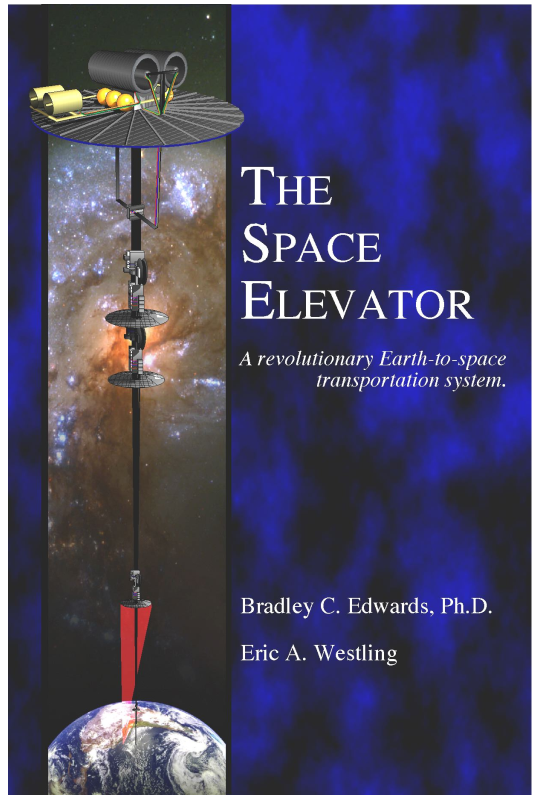
Part of the problem is an acceptance and familiarity issue. The program requires substantial funding. Substantial funding implies a large funding institution. Large funding institutions (governments, professional investors, banks) are generally conservative and slow-moving. In general, such institutions shy away from anything new, unique, different or revolutionary. Not until an idea is generally accepted by the public will such institutions have enough confidence that it is mature enough for their attention.

Dissemination of data

The work that has been done is complex and extensive. This final report covers much of what has been done but does not contain all of the details. To aid in dissemination of the data, designs and conclusions we have published a book (softcover, 288 pages) that is now publically available. Princeton University Press had been enthusiastically pursuing publication of the work but due to the long timescales they required, availability in November 2003, we decided to use a small publisher dedicated to a rapid turn around. The book will be available through the Internet and plans are being made to have it on shelves at chain book stores and Amazon.com.

In addition to the book more recent work is being compiled into smaller concise write-ups that will be available.

<u>*The Space Elevator*</u> <u>Book</u>



The NIAC Phase I report generated by the space elevator program was 85 electronic pages with many images and plots. This report became very popular with the general public after the publicity that we have had. As a result it has been downloaded thousands of times by individuals around the world. With such interest we decided it would be best to publish the report for the general public in a hardcopy form. The initial thought was to publish the report in only a slightly modified form. This was not to happen however.

Several publishers, on-line and traditional, were approached with various degrees of success. Some of the publishers were interested but the number of graphics created problems. Eventually we were dissatisfied with the options available.

At this point Eric Westling, a technical writer, contacted us stating he was interested in reworking the book for the broader general public and pushing to get it published. Since we felt publishing our results was important but secondary to the technical work underway we accepted Westling's offer.

Westling and Edwards worked on rewriting the book for a year, adding new material from Phase II, adding material on social impacts and making the material more readable for a general audience. The book covers all of the technical aspects of the design, deployment and operation of the space elevator in enough detail to illustrate the challenges and the solutions. The book then covers the possible applications and some of the future social impacts of constructing the space elevator. The purpose of the book is to get the information on the space elevator distributed and make a serious, solid case that the space elevator is viable. By distributing as much of the information as possible we will encourage others to begin research in specific areas, get the media and public talking about the program and generate real interest in constructing the first elevator.

At completion the book is now 288 pages, 6x9 inch softcover, with roughly 50 images and plots and covers much of the material from Phase I and Phase II though much of what is in this final report was left out due to scheduling. Princeton University Press was pushing hard to publish the book promising to place it on the cover of their catalog and heavily promote it however their publishing timeline was over a year making the book unavailable until the very end of 2003. This was unacceptable so we self-published through a small printer and have made the book available now, January 2003. Though we have probably sacrificed some publicity and book sales we felt the time criticality of the program was more important. The book will be available through our website and Amazon as well as national book stores.

Initial reviews by technical and non-technical individuals has been extremely positive. Statements include: very readable and understandable, amazingly complete and detailed, will be the bible for the field (Robert Forward), ...

Roughly 100 copies of the book have been sold and as many have been distributed in the last three weeks. At this point there has been little or no formal promotion of the book. Formal promotion of the book is beginning and we expect a dramatic increase in sales shortly.

<u>Presentations/Publications</u>
During the course of Phase II Dr. Edwards as actively presented this work at various locations. Since the space elevator is not a well-known or accepted concept these presentations are critically important. Over the last two years Dr. Edwards has presented this work to NASA HQ, AFRL, NRO, congressmen, universities, private aerospace companies, highschool students, 3rd and 4th graders and the general public. Some of these presentations are listed below.

- Invited talk at the National Space Society meeting (ISDC 2001) in Albuquerque, May 24-28, 2001. The most memorable endorsement was by Arthur C. Clarke during his video address at the banquet.
- Response to the USRA Human/Robotic Exploration of the Solar System RFI.
- Invited talk at the University of Montana
- Invited talks at SPIE Photonics West conference.
- Invited talk at University of California - Berkeley
- Invited talk at local National Space Society
- Session Chair and Invited talk at the Space and Robotics 2002 conference
- Invited talk at the Harvard-Smithsonian Center for Astrophysics in Boston. It was the largest audience they have had for a talk and was very well received.
- Invited talk at the Futuristic Space Technologies Conference in Trieste, Italy
- Presentation to the Air Force Space Missile Center.
- Invited talk at the NASA Aerospace Technology Working Group meeting
- Participation in the NIAC conferences.
- Two presentations at the Museum of Flight in Seattle, one to about 30 nine to eleven year olds and staff and a second to 20 high school students.
- Meeting with Bryan McConaughy of Norman Dicks' office
- NASA HQ: We met with Gary Martin, Harley Thronson, Moore, and Giulio Varsi and Mike Salamon.
- Congressman Norm Dicks
- Senator Gibbons
- DARPA
- BP Solar: Interested in restarting their solar power satellite program based on our effort.
- NRO
- Space Transportation Association
- Lockheed Martin
- National Space Society
- National Defense University

- FCC
- FAA
- Aon Insurance
- Have begun preparation for the IAF Vancouver 2004 IAF Symposium where there will be a session on space elevators
- Invited talk at ASGSB
- Future invited talk at this summer's Space Studies Institute meeting in Princeton.
- Dr. Edwards has also give five talks to local Seattle groups interested in technology
- Organizer for Space and Robotics 2005 which will concentrate on the space elevator
- Invited talks at Bremen Germany at the 2003 IAF meeting
- Invited talk for NSA on March 20, 2003
- Invited by National Space Society to brief members of the House and Senate at a luncheon on March 21, 2003.

Independent of our effort but encouraged by it, several senior thesis and student presentations and investigations have begun on various aspects of the space elevator. We have consulted/mentored on these efforts.

Media/Promotion

The biggest surprise to us during the Phase II effort was the media attention we received. It started small with a few Space.com articles and then spread and snowballed into a substantial media frenzy. This took time away from the technical effort and reduced some of what we were able to do technically but the media attention has undoubtedly helped move the concept forward.

As a starting point, we had noticed at a NIAC conference a very good animation used by the ornothopter program. As a result we created several animations showing the deployment of the space elevator and later how a space station, Mars elevator and solar power satellite deployment might look using the space elevator concept. These video clips have helped dramatically in relaying the concept to a new audience. In addition the video clips have helped us to visualize the system designs and how the components will work together.

JAY LENO

NASA is giving $600,000 to a Seattle company to explore the possibilities of building an elevator to space. What would that be like? How many John Tesh albums do you have to listen to on that thing?

At the end of 2001 some attention started to appear due to several technical presentations. Dr. Edwards and the space elevator concept were featured on Canadian NPR, *Quirks and Quarks*, were the subject of several Space.com articles and then appeared on NPR's *All Things Considered*.

Early in 2002, a TechTV interview was held in conjunction with an SPIE conference. The show did a good job of reporting on the concept though the small cable audience didn't create any real momentum but was picked up by ABCNews.com and affiliates. Around this same time since we were starting to get attention at different levels we created some artist images of the system from the schematic drawings on hand. These images have been very popular throughout 2002.

In July of 2002, in an effort to get more attention focused on the effort we contacted the local newspapers. The Seattle Times immediately jumped on the story, placed it on the cover above the fold and sent it out on the wire. As a result of this exposure, Dr. Edwards did roughly a dozen live radio interviews and three TV interviews including one live for CNN. Within a month, the story on our effort appeared over 150 times on radio and TV around the world including BBC, CNN and each of the major networks. We have no numbers on the distribution of the newspaper report though have had reports that the paper coverage was at least as widespread as the radio and TV. All of the press was uniformly positive.

On the tail of the initial burst of media attention we held a conference on our effort in Seattle. Stories on the conference ran on Space.com, MSNBC and the front page of the Canadian *National Post* (300,000 subscriptions, 1 million readers). This media created a large amount of public interest and on august 13th our website received roughly 30,000 visitors. In addition to the conference media we also had three BBC spots (two live and one heard at least as far as Lebanon) at this time.

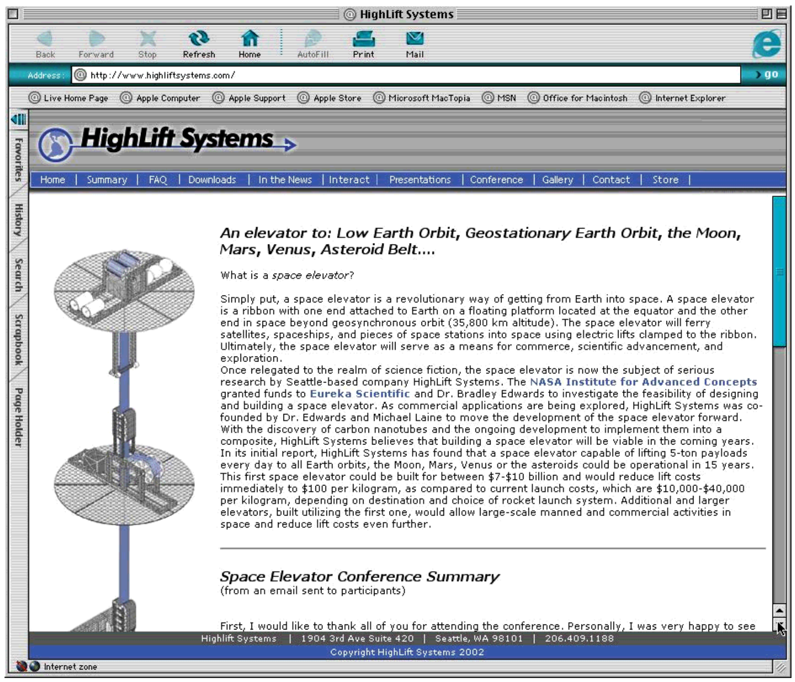
In October, 2002, we worked with BBC to produce two interviews and a four-minute feature on our program that appeared worldwide and reached 220 million households. We also appeared on the cover of Science News' October , Europe's *Focus* magazine and the radio show, *The Space Show*.

Over the last three months the media coverage has oscillated between quite and frenzied weeks. We have appeared on the cover of *Science News* and *Ad Astra*, will be a feature story in *Wired* magazine, mentioned in the *New York Times*, continuing radio, TV and newspaper interviews from across the U.S. and as far away at western Australia.

This is an overview of the media attention that has occurred. It has all been positive and shown the program in an extremely good light. As a result of the media we have been able to foster better and stronger connections with people who make decisions and attract the help that the program has needed. But the primary, long-term benefit that the media attention will have is to get the space elevator concept into the public mind. No large program, no matter how developed or valuable, will be accepted until the public is well aware of its existence and is discussing it.

The latest public attention has been a result of the Columbia shuttle tragedy. People want to have a space program and to a large extent our space program is the world's space program. Recently on the news, during discussions of the tragedy, numerous individuals were stating "we" must continue the space program and "our" space program. These comments were made by people living both inside and outside the U.S.: NASA has become the world's space program. Because of the desire to continue and to make it something better people have begun to look at the space elevator as a viable alternative to rockets. This media attention, though a result of a tragedy, will likely propel our program forward.

<u>Websites on the Space Elevator</u>



Our effort has attracted a lot of public and media attention and eventually we realized that we had to put some effort into producing a webpage to distribute the information we were generating and keep people informed of our progress.

We found several individuals who were interested in helping develop the space elevator and wanted to produce a webpage for us. We supplied them with material and some support and they produced a set of pages for us. The complete website (www.highliftsystems.com) contains links to published documents, images, video clips, message boards for discussions, FAQ page, summary of media coverage, and contact information. It has been a very popular site with gigabytes of material being downloaded from it by tens of thousands of individuals. A second smaller website, www.eurekasci.com/SPACE_ELEVATOR/Space_Elevator_Homepage.html, has also been set up.

In addition to distributing information, the website has collected information on public interest, brought in collaborators, and spawned lively discussions on the space elevator design. References and links to our webpage have propagated through the web and into many areas of discussion.

As a result of our space elevator conference several news articles ran including one at Space.com that was picked up by MSNBC and a front page article in the Canadian National Post (300,000 subscriptions, 1 million readers). This media created a large amount of public interest and on August 13th our website received 520,000 page requests. Since that time our site has continued to be very active with thousands of page requests each day.

Space Elevator Conference 2002

In an effort to distribute our results, get input from the community and foster additional research in this area we held a conference on the space elevator. The conference was at the Sheraton Hotel in downtown Seattle on August 12th and 13th, 2002. The two-day conference covered technical, legal, health and financial issues related to the space elevator.

Since the space elevator does have a popular science fiction past we were concerned that an open conference could result in a large conference focusing on the science fiction aspects and not examine the program or designs at hand. Very limited conferences of invitees can also result in biased discussions of limited use. With these aspects in mind we strove to attract people from public, private and academic institutions with detailed knowledge of aspects related to the program but not specifically involved in the program. A fair fraction of the attendees had only an introductory understanding of our specific designs and were given detailed designs and write-ups prior to the conference. The organization and activities related to the conference were substantial but well worth the result.

The conference schedule below covered all technical and non-technical aspects of the program.

Welcome	Bradley C. Edwards: Eureka Scientific/HighLift Systems
Keynote address	Lauren Edgar: High School Student
NIAC Space Elevator Concept	Bradley C. Edwards: Eureka Sci./HighLift Systems
CNT composite status	Tom Tiano: Foster-Miller
CNT composite status	Rodney Andrews: University of Kenticky
CNT composite status	Mathieu Grac: Nanoledge
CNT composite status	Li Feng: China
Ribbon Design	Bradley C. Edwards: Eureka Sci./HighLift Systems
Tethers	Robert Hoyt: Tethers Unlimited
Tether dynamics	Haym Benoroya: Rutgers University
Power beaming	Hal Bennett: Compower
Climber & Spacecraft	Chuck Rudiger: Lockheed Martin
Anchor station	Eric Anderson: Art Anderson Associates
Tall Towers	Geoffrey Landis: NASA Glen
Meteors	Nick Johnson: NASA
Lightning, At Ox, wind, terrorists	Bradley C. Edwards: Eureka Sci./HighLift Systems
Environmental impact	Russell Potter: Owens-Corning
Applications	Bryan Laubscher: los Alamos National Laboratory
Development yet required	Bradley C. Edwards: Eureka Sci./HighLift Systems
Budget	Eric Westling
Managing large programs	Tom Ho: T.Y. Lin International
Financing the endeavor	Michael Laine: HighLift Systems
Legal: operations	Gabrynowics: Space Law Center
Legal: operations	Schwetje: Pierson Burnett LLP
Launch Markets	Bill Harris: Lockheed Martin
Legal: financial	Robert Van Cleve: HCMP LLP
Private investors	Barry Thompson
Public investment	Chris Petrella
Round Table Discussion	Edwards and Laine

As can be seen by the schedule, the conference was very focused. It was not like many large conferences that have presentations on numerous fields of study. This focused approach allowed us to attack questions in detail and get all participants up to speed and become vital parts of the discussions.

There were 63 total attendees including people from NIAC, two governor's offices, prominent private companies, Universities, NASA, ESA, and as far away as China. The comments back from the participants were very positive. The unofficial consensus was that the space elevator would be viable in the near future (operating in 15 to 50 year timescale) and that there were no showstoppers. The conference helped solidify some collaborations and create a number of new ones. Many of the conference participants who were not involved in the program prior to the conference approached us about becoming involved.

Generally keynote addresses are made by people with impressive titles. We selected Lauren Edgar, a high school student who has no title, to give the keynote for a very good reason. She is part of the generation that will be most affected by the focus of the conference. Her generation, our children, is who this is for. Miss Edgar's speech to kick off the conference did inspire and motivate the participants. The enthusiastic participation and progress that was made at the conference speaks well for handing the legacy of the space elevator to the coming generations.

The presentations from the conference have become part of our webpage (www.highliftsystems.com) for further reference.

An important part of the conference was in bringing together the participants. AS many as ten new collaborations formed at the conference and substantial information was exchanged. A few examples of the collaborations include:

- Rodney Andrews, University of Kentucky, and Margaret Roylance, Foster-Miller Inc., will be having discussions because it appears that they each have solutions for problems that the other has been struggling with. This meeting alone may have moved the CNT composite development quickly forward another five steps.
- David Raitt from ESA has agreed to be the ESA contact and recruit and orchestrate European efforts that can assist the program.

The technical aspects of the program were discussed thoroughly but other equally critical areas arose and mark the beginning of a new set of efforts. Legal and funding issues are obviously at the top of this list. The full investigation of these will be covered elsewhere in this report.

Follow-On Efforts

The future of the space elevator has improved dramatically over the last three years. In 1999 the concept had been all but discarded, now it is seriously being discussed as a future replacement for the shuttle. With this rapid development, the program has entered a continuous state of flux. The initial designs have been laid out. The problems and challenges quantified along with possible solutions for all. The deployment scenario has been put together and so has the basic schedule and cost breakdown. A framework for the system and further work is complete. This work has also demonstrated that there are no hard reasons why the elevator can not be built in the very near future. The work has gone one step further to show that the space elevator can be built.

Having said that, where do we go from here? On the technical side:

- The carbon nanotube composite development needs to be funded and continued. This will take two years and somewhere between one and ten million dollars to complete depending on how easy various steps are. Over the last few months the work has progressed better than expected so development costs could be on the lower end of the estimate.
- Full engineering designs need to be completed. Our work has put together overview designs and integrated existing systems. Further studies need to be completed to ensure proper integration and complete designs of critical and new components such as the traction drives.
- Test of engineering designs and one or more feasibility tests need to be performed. Any new or innovative designs need to be fully tested either individually or in a complete system prior to beginning construction. This could entail our proposed feasibility test along with several other space tether and ground tests.

On the non-technical side:

- Financing needs to be acquired. Financing for the engineering development is the most difficult. Various venture capitalists have expressed an interest in funding the carbon nanotube composite development. Funding the space elevator development may require federal funding due to the longer timescale.
- Legal and regulatory issues need to be addressed. We have touched on these but further effort in this area is required.
- Political issues need to be overcome. There will be lobbying against the construction of the space elevator because it will threaten conventional launch systems. There will also be international issues that need to be addressed.
- Participate in conferences being organized on the space elevator (Space and Robotics 2005, IAF 2004, LANL workshop, possible Nikkei & Toyota sponsored Japanese conference, ESA meeting, …)

We plan to continue pushing the program by:

- Organizing conferences, meetings and workshops on the space elevator.
- Pursue follow-on funding through federal agencies, private investors and congressional means.
- Create a popular following for the concept through the media.

- Aiding any respectable entity that is moving forward on the development. This includes the European Space Agency, the Japanese space agency, the Australian government and private entities.

To continue this effort, HighLift Systems was formed. It is conceivable that further funding will be secured through HighLift Systems to move both the space elevator and carbon nanotube development programs forward. Initial funding can be leveraged to acquire additional funding through various sources. It is also possible that the effort might be moved to another institution for continued work. Possible entities include but are not limited to Lockheed Martin, MSFC, Los Alamos National Laboratory, and the European Space Agency.

However, there are many different ways that this program may progress and one possible option that has been examined and appears likely at this time is a complete change. Dr. Edwards has accepted the position of Director of Research at the Institute for Scientific Research (ISR) in West Virginia. The institute works on basic space, detector, engineering, flight simulation and software developments and has a technical staff of approximately 60 that may grow to around 200 in the coming years. ISR wants Dr. Edwards to bring the space elevator there along with several of his other programs and will support them with both internal funds and its strong political connections. At the Director of Research position Dr. Edwards will be responsible for all aspects of the research and technical staff at ISR. This is an ideal position with the resources to back it up to push the space elevator forward.

Summary

Over the past three years we have examined all aspects of the space elevator concept. A completely new design was proposed for the space elevator, it incorporated few characteristics of the earlier designs. We broke down this design into component parts and attacked each individually. The ribbon was designed to optimize performance and stay within the limits of the materials being developed. The deployment was reduced to conventional large rockets and standard spacecraft hardware. The climbers utilized off-the shelf technology to achieve a high payload fraction and to enable build-up of the ribbon. We solved the power problems anchor questions and addressed and solved each of the operational challenges. This we then put into a complete package with scheduling, testing, development and cost estimates.

We initially concentrated on the technical aspects laying out a viable plan for constructing, deploying and operating the system. We proceeded to fill in the details, clean-up and optimize the design and push into the non-technical areas like legal, health and finance. After having completed a thorough study of the concept and all the implications we then began promoting the idea. The media and public appear to be excited about the concept and the publicity has spread globally through very reputable channels.

Our book lays out most of the technical details though many could not be included due to limits on sizes and the patience and interest of readers. The massive amount of information, design details, computer programs, failed and successful studies, tests, etc. related to our effort on the space elevator can not easily be disseminated but will be used in our continuing effort and hopefully be fully compiled for wide distribution. The information distributed to date has already created many new research groups and efforts around the world and we suspect that this effort is only the beginning. Dr. Edwards and his assembled team will continue their work through various funding resources with the focus being the Institute for Scientific Research in West Virginia where Dr. Edwards has accepted a position as Director of Research.

Three years ago the space elevator was science fiction. Because of NIAC funding the space elevator is now a viable system that is well on its way to becoming reality. The return on the $570k NIAC investment could eventually become trillions of dollars annually and provide an energy-starved world with clean unlimited power, dramatically improved communications, new resources, new worlds to live on and the ability to understand our planet and the solar system around us at a level impossible with conventional rockets.

Topic: **The Space Elevator: A Brief Overview**

Point of contact: Bradley C. Edwards, Ph.D. Tele(before March 24,2003): 206-409-1188
Director of Research Tele(after March 24,2003): 304-368-9300
Institute for Scientific Research E-mail: brad_edwards@yahoo.com

The space elevator first appeared in 1960 (Artsutanov) in a Russian technical journal. In the following years the concept appeared several times in technical journals (Isaacs, 1966; Pearson, 1975; Arthur C. Clarke, 1979) and then began to appear in science fiction (Arthur C. Clarke, 1978; Stanley Robinson, 1993). More recently, 1999, NASA held a meeting to examine the possible design of a space elevator (Smitherman, 2000) The simplest explanation of the space elevator concept is that it is a ribbon with one end attached to the Earth's surface and the other end in space beyond geosynchronous orbit (35,800 km altitude). The competing forces of gravity at the lower end and outward centripetal acceleration at the farther end keep the cable under tension and stationary over a single position on Earth. This ribbon can be gently ascended or descended by mechanical means to or from Earth orbit or used as a sling to deliver payloads to neighboring planets.

Funded by a NIAC grant, we have defined a complete space elevator that can be constructed, deployed and operated using current or near-term technology. In our scenario an initial ribbon (8 inches wide and thinner than paper) is deployed using four expendable launch vehicles and conventional satellite technology. The initial ribbon with one end attached to an anchor platform and the other 62,000 miles up in space will be enlarged using mechanical climbers. Each climber will ascend the ribbon and add to it until a complete elevator is achieved. The final system will have a ribbon that is three feet wide and thinner than paper, an ocean-going anchor platform located in the eastern equatorial Pacific, a laser power beaming system, a debris tracking system and mechanical climbers capable of delivering 13 ton payloads to any Earth orbit or the neighboring planets. The total capacity of the system will be roughly 1000 tons per year at an operating cost of $100/lb to any Earth orbit, or location between Venus and the outer asteroid belt. The complete system has been designed with solutions for all of the major challenges. **The estimated construction cost is $10B and can be operational in 15 years.**

The ribbon, being the only component of the space elevator not commercially available, is the last hurdle prior to construction of the space elevator. The sheer length, 62,000 miles, is considerable but is well within current technology. The material required for construction of the cable is a carbon nanotube composite: currently under development and will be available in 2 years.

The space elevator would allow for the launch of large fragile structures such as solar power satellites to provide clean renewable energy to Earth, unsurpassed Earth observation possibilities for intelligence and military applications, commercial manufacturing facilities, inexpensive stations for manned activities, and payloads for exploration and development of space.

Current strategy calls for $40M in development funds over the next two years with construction beginning immediately following this design stage. We have briefed NASA HQ, Chief Technologist at AFRL, FAA, FCC, Aon Insurance, members of the House and Senate, and held a conference that dealt with all aspects of the space elevator from technical to legal and finance. Our effort has been reported on CNN, BBC, radio programs, TV spots and newspapers around the world. Our program has also been on the covers of *Science News*and *Ad Astra* and will be featured in the April *Wired* magazine.

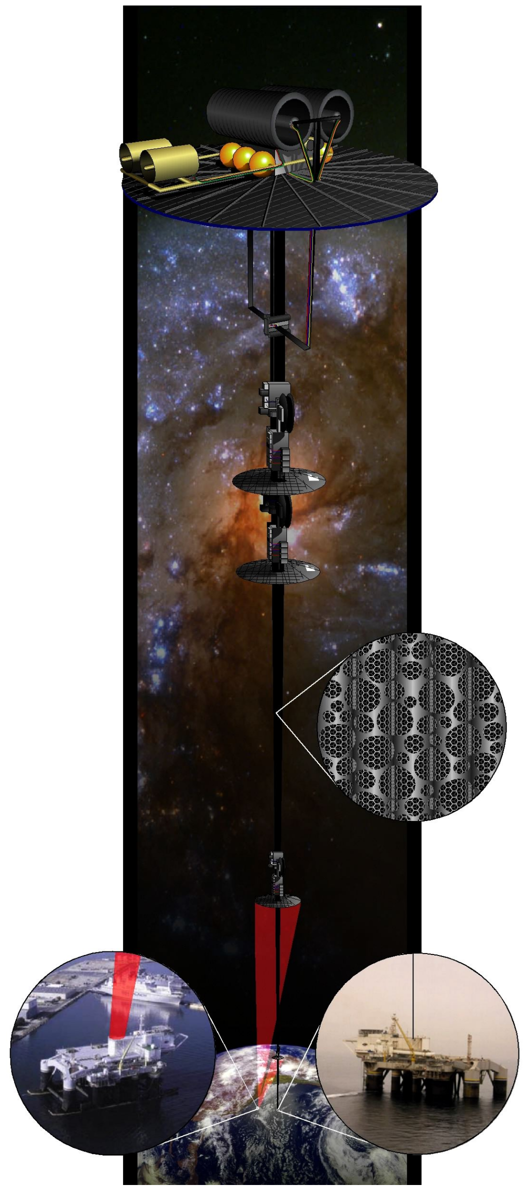


Figure 1. Artist conception of the proposed space elevator.